The India based Neutrino Observatory project

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Plan of talk

1. The India based Neutrino Observatory project
2. Physics reach of Iron Calorimeter detector
3. ICAL magnet, RPCs, Electronics

1. INO : Underground lab for ν physics, searches for dark matter, 0ν2β decay

Physics Goals of Iron Calorimeter detector

- Measure atmospheric ν_μ , $\bar{\nu}_\mu$ [resolution of anomaly by SK in 1998; Physics Nobel 2015]

- Address ν-mass hierarchy (normal or inverted) ⇒ whether m_3 **greater or smaller** than m_1, m_2

- Together with accelerator based experiments search for CP-violation (**matter-antimatter asymmetry!**)

Other experimental possibilities at INO

- Neutrinos = Anti-neutrinos? (Dirac vs Majorana)

  Search for $0\nu2\beta$ decay in ^{124}Sn – TINTIN (TIFR-BARC-IIT(R)-Lucknow)

- Search for **Dark Matter** particles

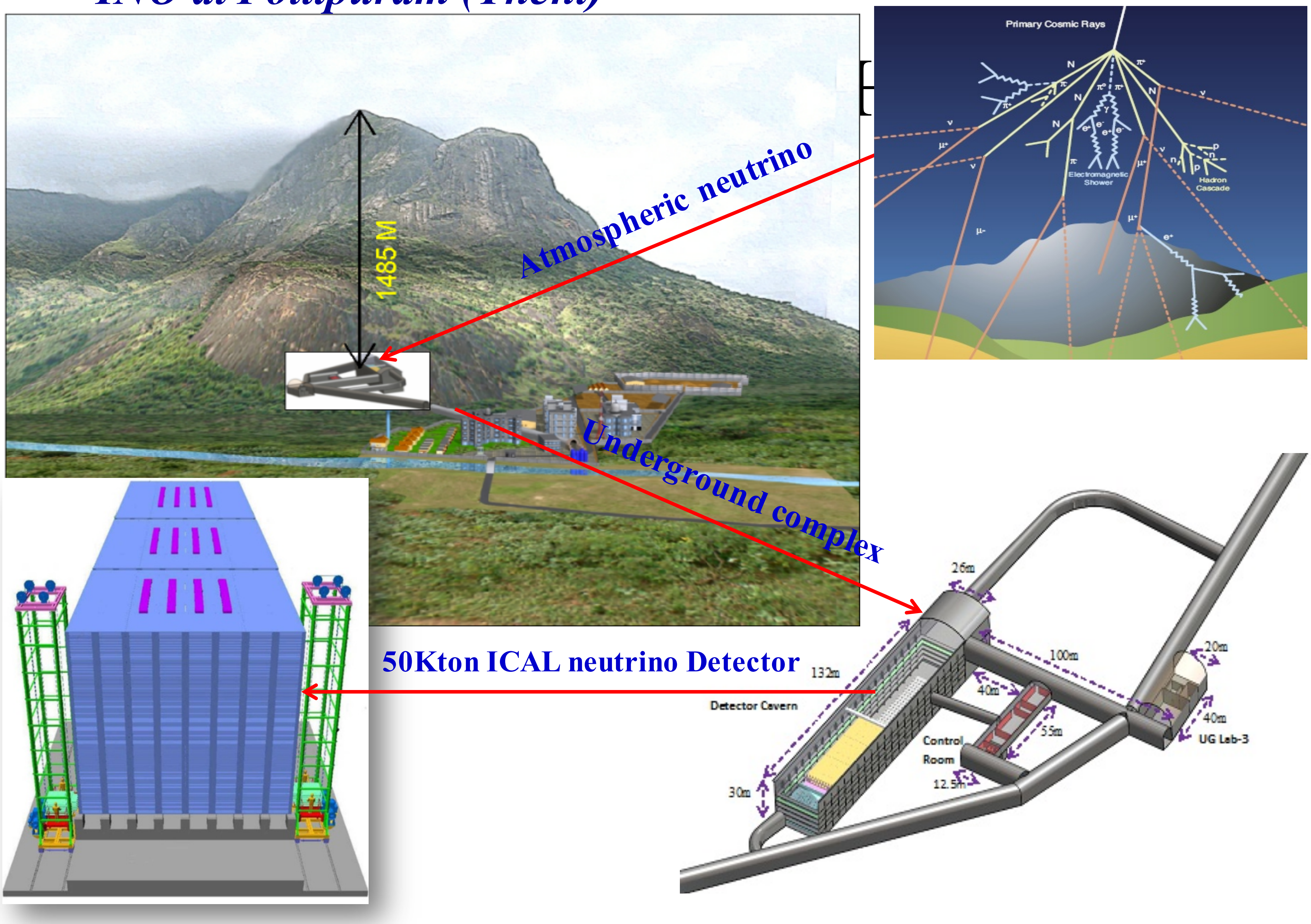
  DINO – cryogenic Si bolometer (SINP-Texas)

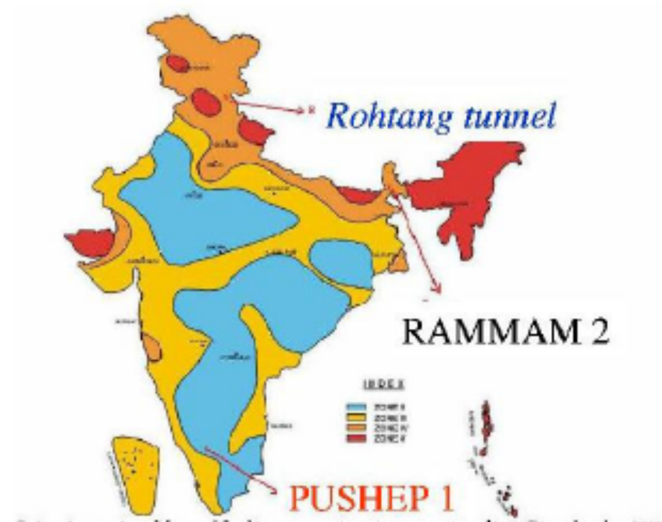
- Nuclear astrophysics (reactions @ E_{Gamow})

  Low energy high current accelerator

  (Universities working on proposal)

INO at Pottipuram (Theni)





Seismic zoning Map of India- issued by Bereau of Indian Standards, 2000

BWH (9°58' N, 77°16' E)
10 km from Theni (Railhead)
120 km from Madurai(Airport)

IICHEP (Madurai) & INO (Pottipuram)

Compound wall at IICHEP site (12 ha)

Compound wall (E) at IICHEP site

Compound wall at INO site (27 ha)

Water storage tank at INO site

2. Physics reach of Iron Calorimeter detector

ICAL will measure atmospheric muon neutrinos

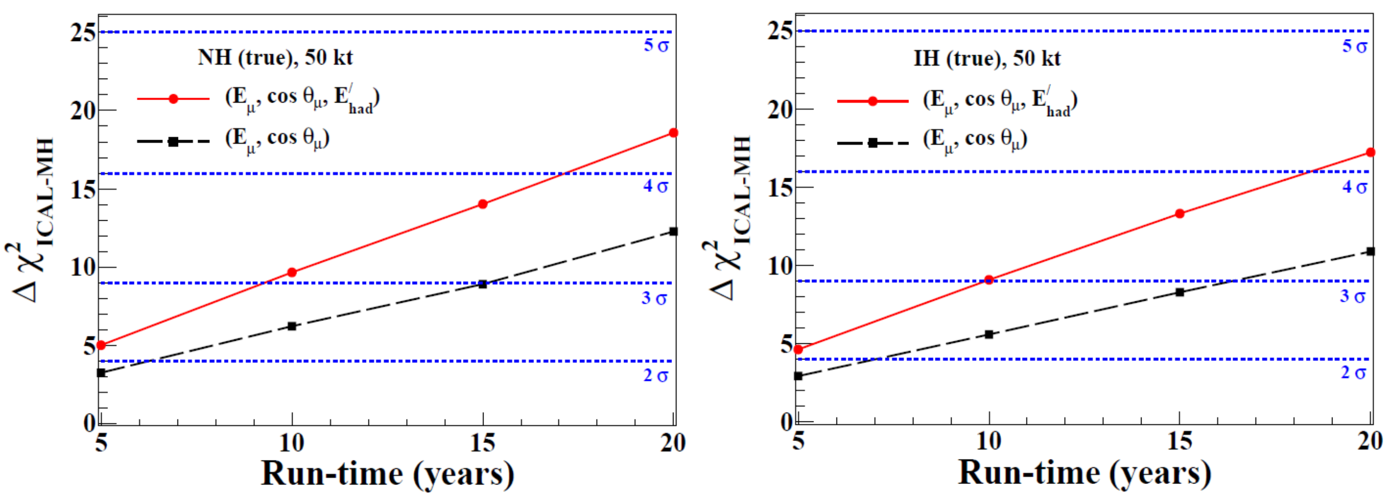
Energy range: 1 GeV $\leq E_\nu \leq$ 20 GeV

Azimuthal angle: $0° \leq \theta_\nu \leq 70°$, $110° \leq \theta_\nu \leq 180°$

- Precise measurement of neutrino oscillation parameters
- Neutrino mass hierarchy – normal or inverted
- Octant ambiguity
- VHE muons
- Magnetic monopole search, light DM decay…

Mass hierarchy of neutrinos – sensitivity of ICAL

- $m_1 < m_2 < m_3$ (NH) or $m_3 < m_1 < m_2$ (IH) ?
- ICAL can identify mass hierarchy using atmospheric $\nu_\mu , \bar{\nu}_\mu$
- With accelerator based expts. can probe CP violation in ν-sector



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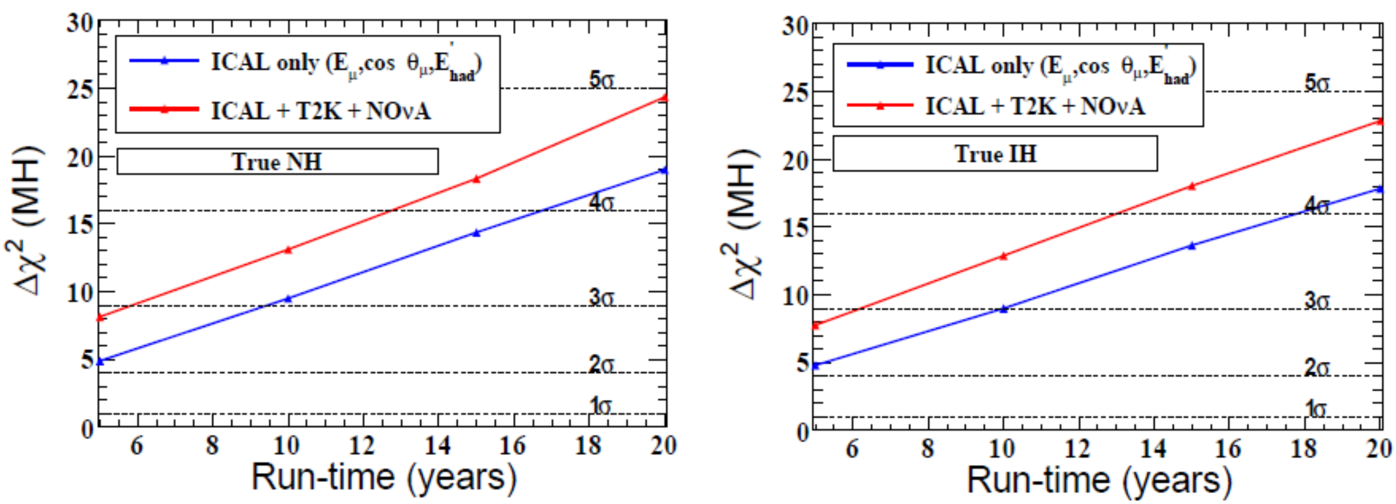
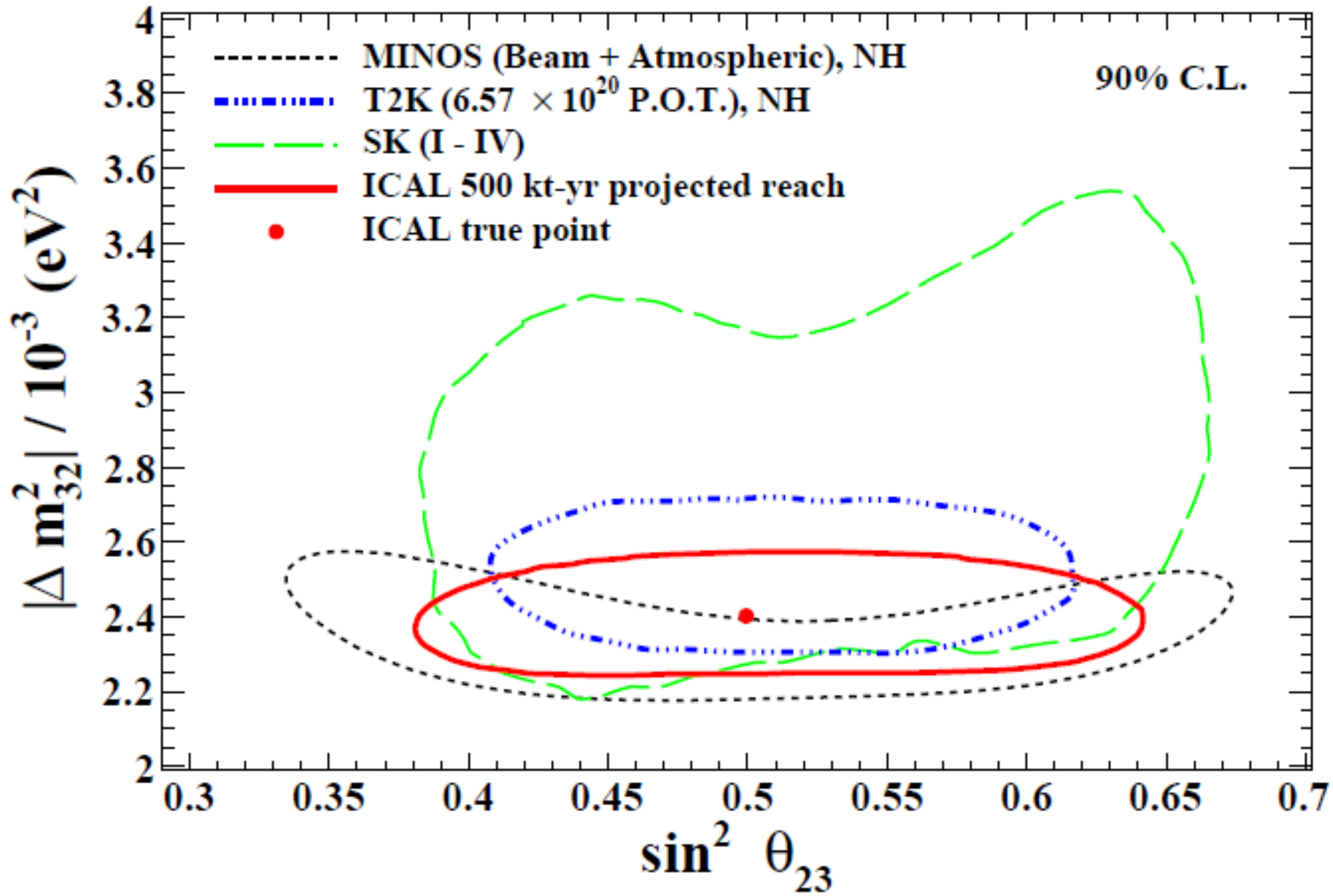


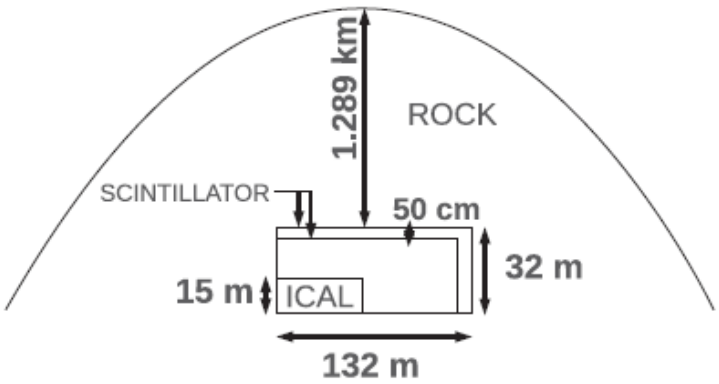
ICAL + T2K + NovA

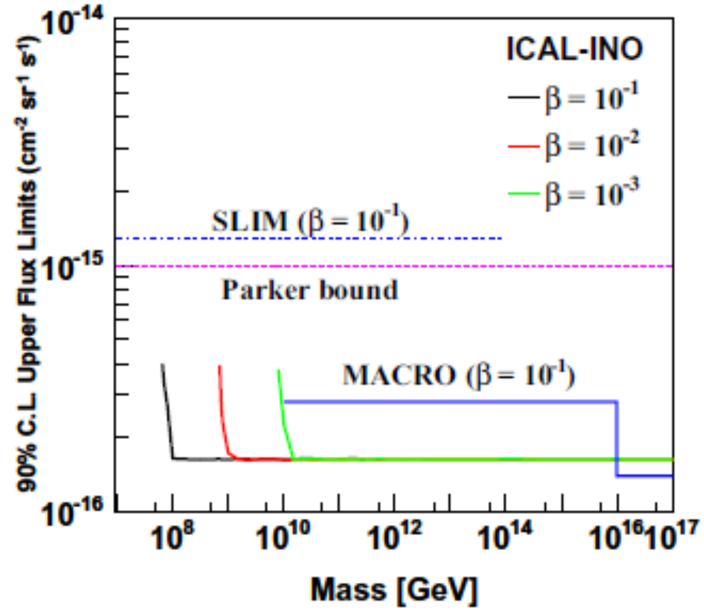
Sensitivity of ICAL for $\sin^2\theta_{23}$ - Δm_{23}^2 plane



Searching for exotic particles using ICAL…

Primordial Magnetic Monopoles





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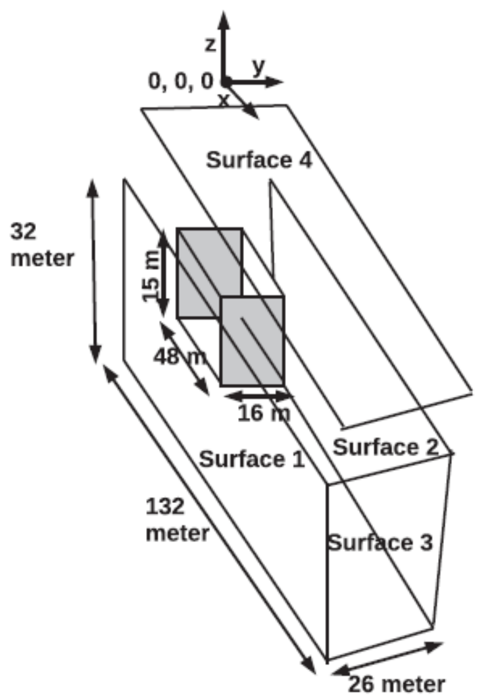
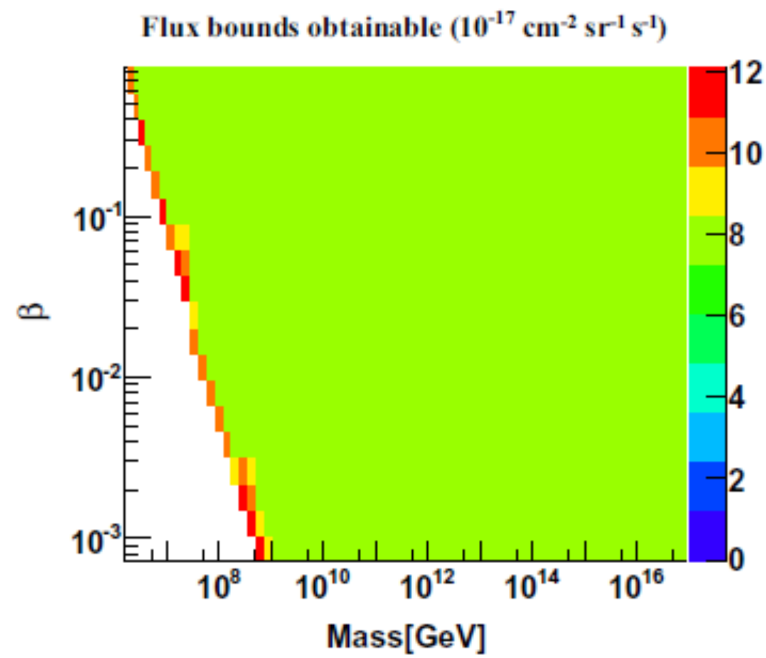




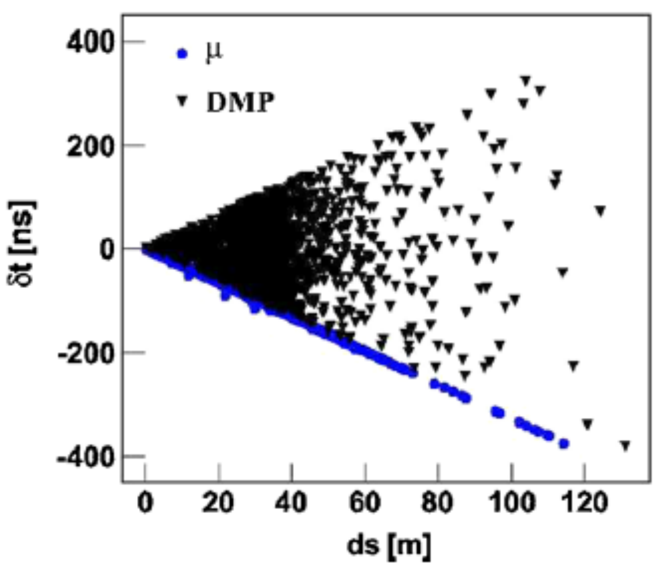
ICAL++

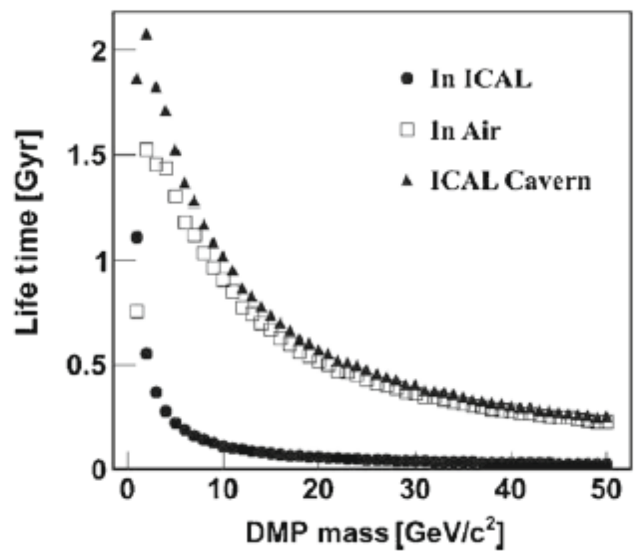
Searching for dark matter (DM) decay to muon pair

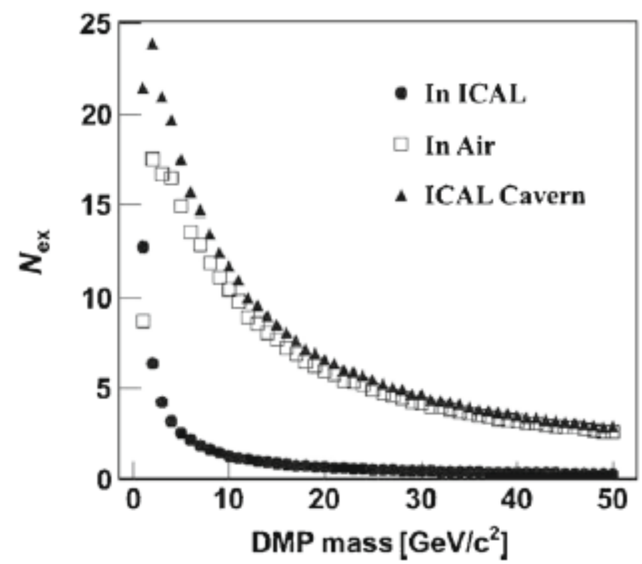
Anomalous events seen at KGF (5 ~1964-1975, 3 ~ 1980-1990) – could arise from decay of light DM (Murthy, Rajasekaran 2014)?

$\Phi_{DM} \to \mu^+\mu^-$ $M_{DM} \sim 1 - 50$ GeV/c^2 ICAL+ sensitivity explored

However if $\Phi_{DM} \to \nu_\mu + \overline{\nu}_\mu$ lower bounds on DM lifetime from existing neutrino detectors much higher (Signal $\propto \int (4\pi\rho_{DM}r^2/r^2)\, dV$





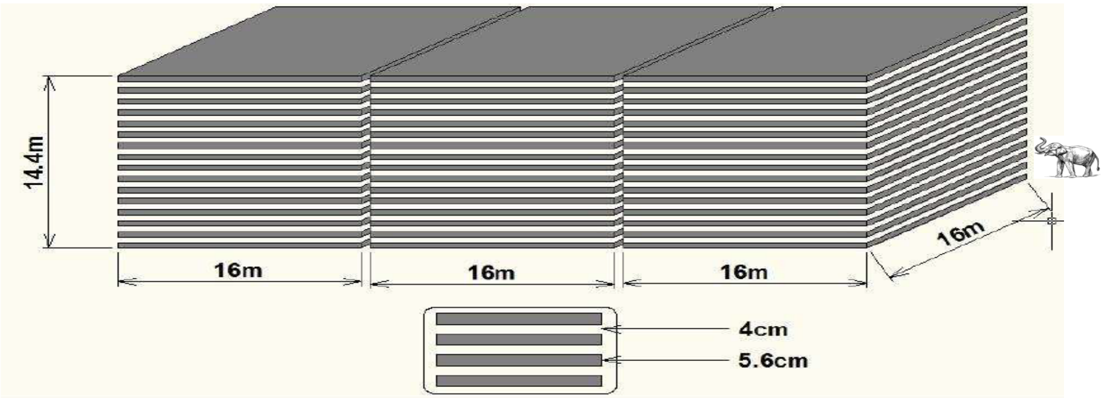


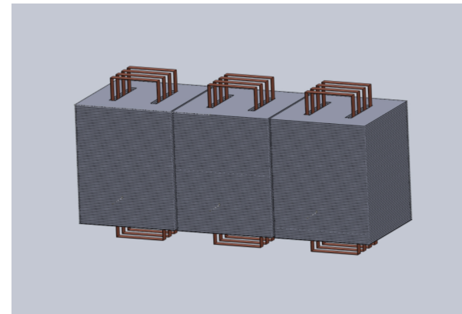
3. ICAL Magnet, Glass RPCs, Electronics

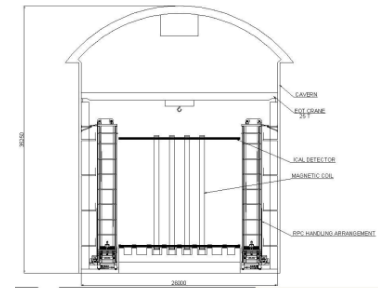
INO-ICAL Detector

Parameter	ICAL	ICAL-Engineering module
No. of modules	3	1
Module dimensions	16.2m × 16m × 14.5m	8m × 8m × 2m
Detector dimensions	49m × 16m × 14.5m	8m × 8m × 2m
No. of layers	150	20
Iron plate thickness	56mm	56mm
Gap for RPC trays	40mm	40mm
Magnetic field	1.3Tesla	1.3Tesla
RPC dimensions	1950mm × 1910mm × 30mm	1950mm × 1910mm × 30mm
Readout strip pitch	30mm	30mm
No. of RPCs/Road/Layer	8	4
No. of Roads/Layer/Module	8	4
No. of RPC units/Layer	192	16
No. of RPC units	28,800 (107,266m^2)	320 (1,192m^2)
No. of readout strips	3,686,400	40,960

Schematic of Iron Calorimeter

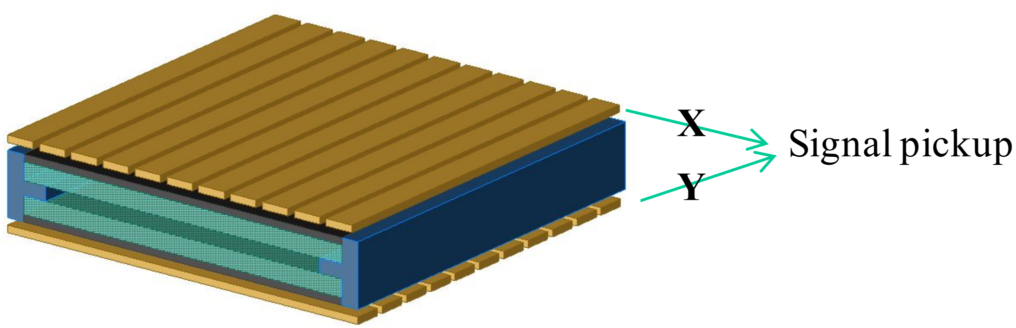




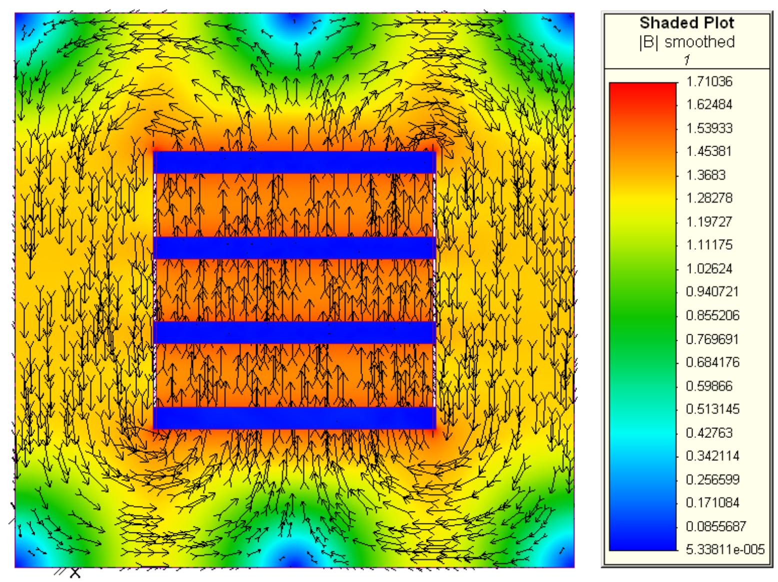


51 kt world's largest electromagnet

3 modules × 17 kton
Each with 150 layers Fe+RPC
B-field > 1 Tesla (90%)

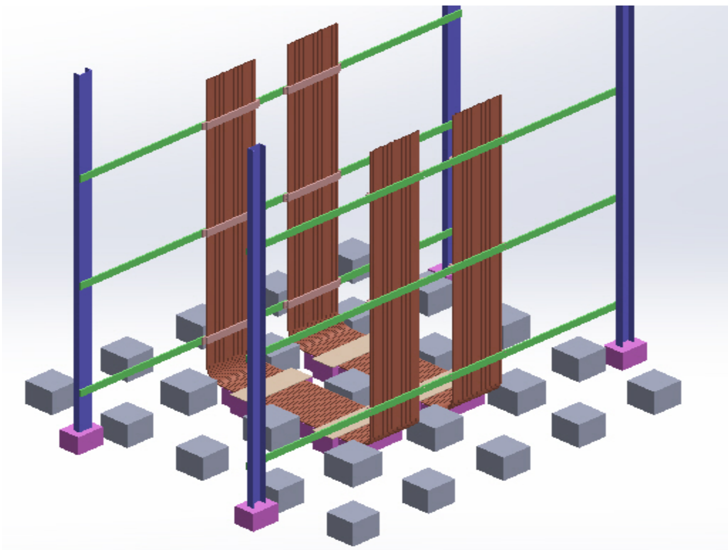


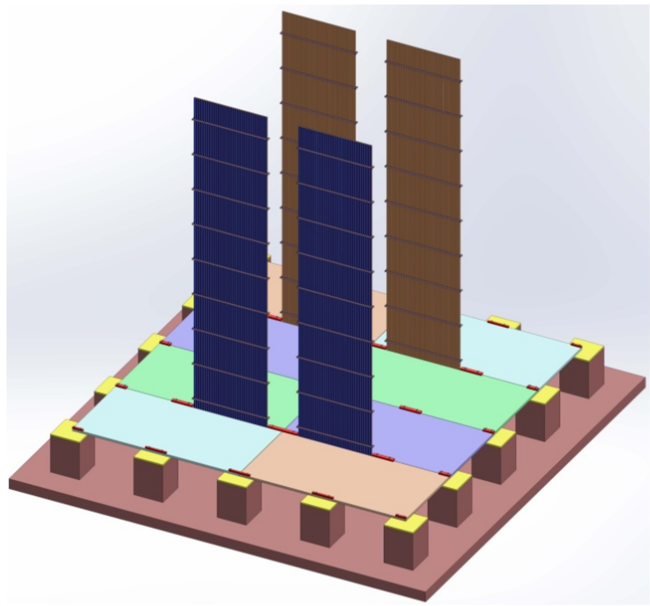
Glass RPC for detecting charged particles
~30,000 RPCs required, ~ 3.8 M channels

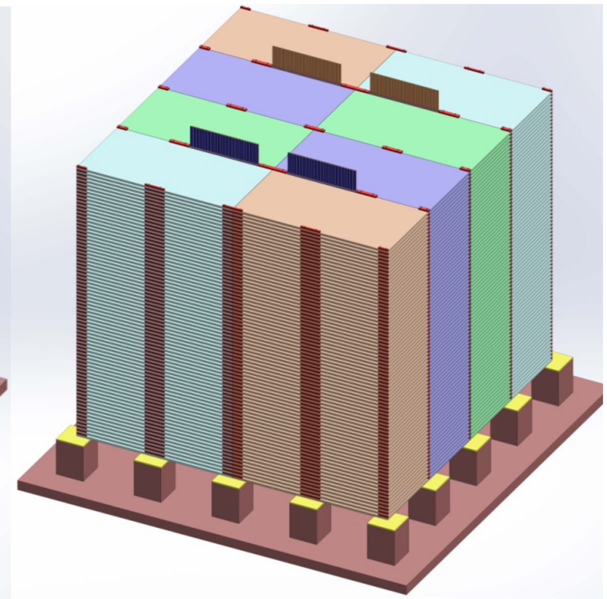


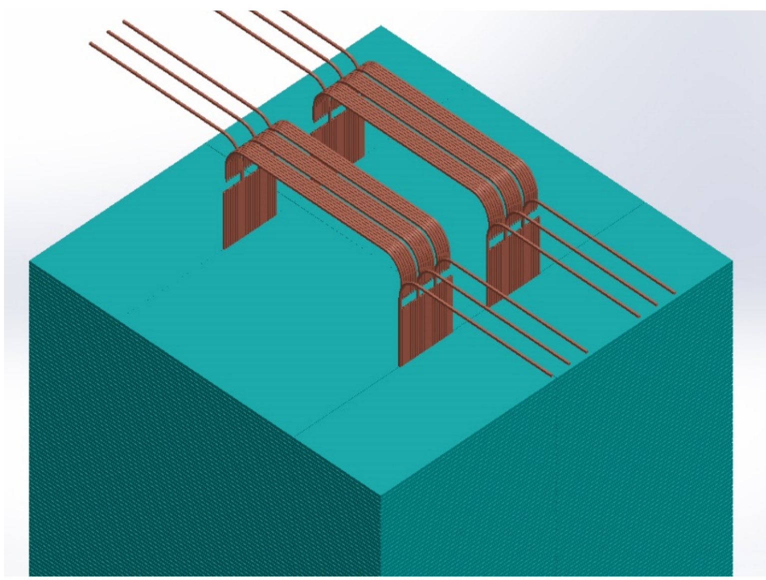
B-field for 60 kA-turns, typical low C steel

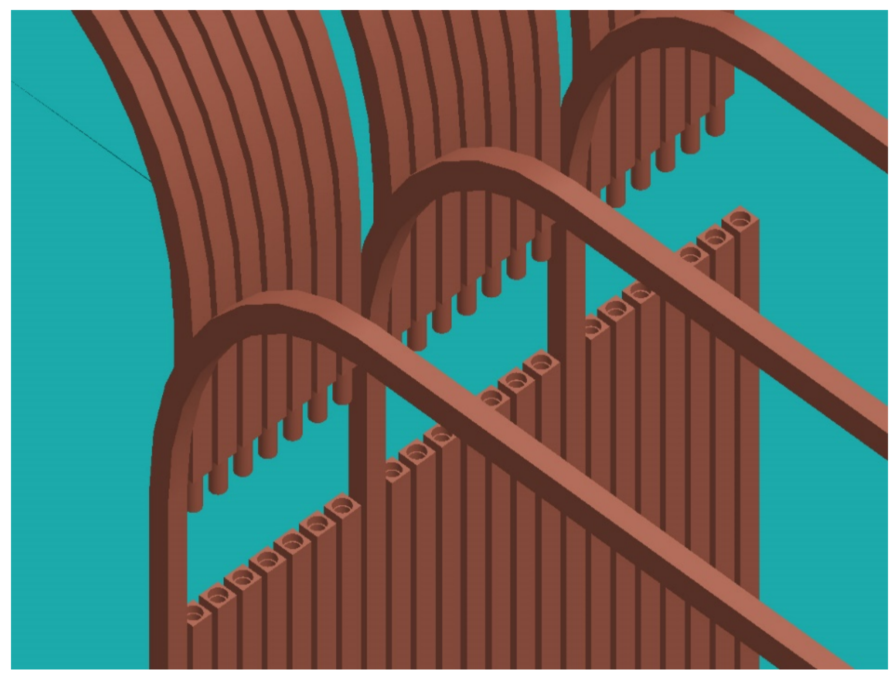
Engg. Module of ICAL at IICHEP (20 layers × 8m × 8m)











Making glass RPCs at TIFR…

Started with
10 cm × 30 cm Glass
RPC in Streamer mode

200 cm × 200 cm

30 cm × 30 cm

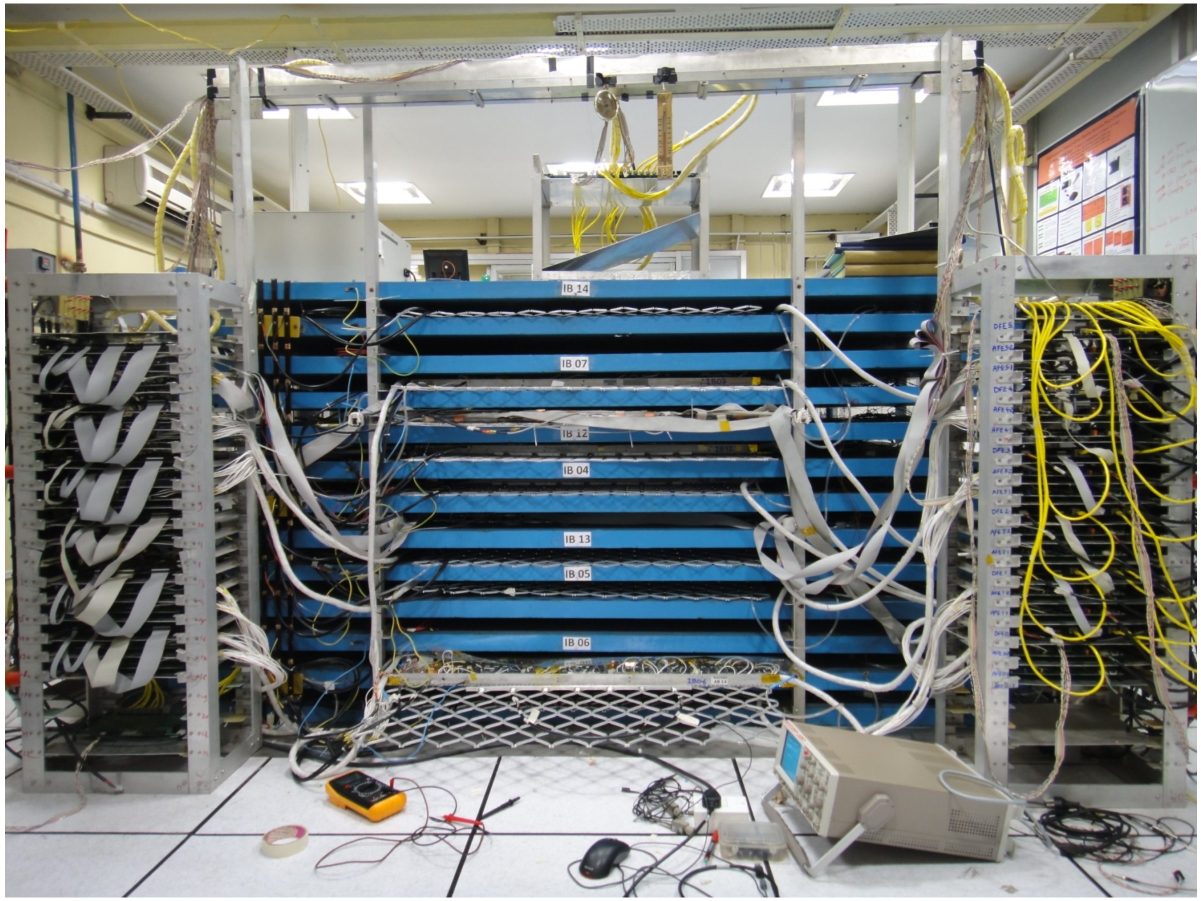
10 cm × 30 cm

100 cm × 100 cm

Now with 200 cm × 200 cm Glass RPC in Avalanche mode

A Prototype Magnet & RPC setup

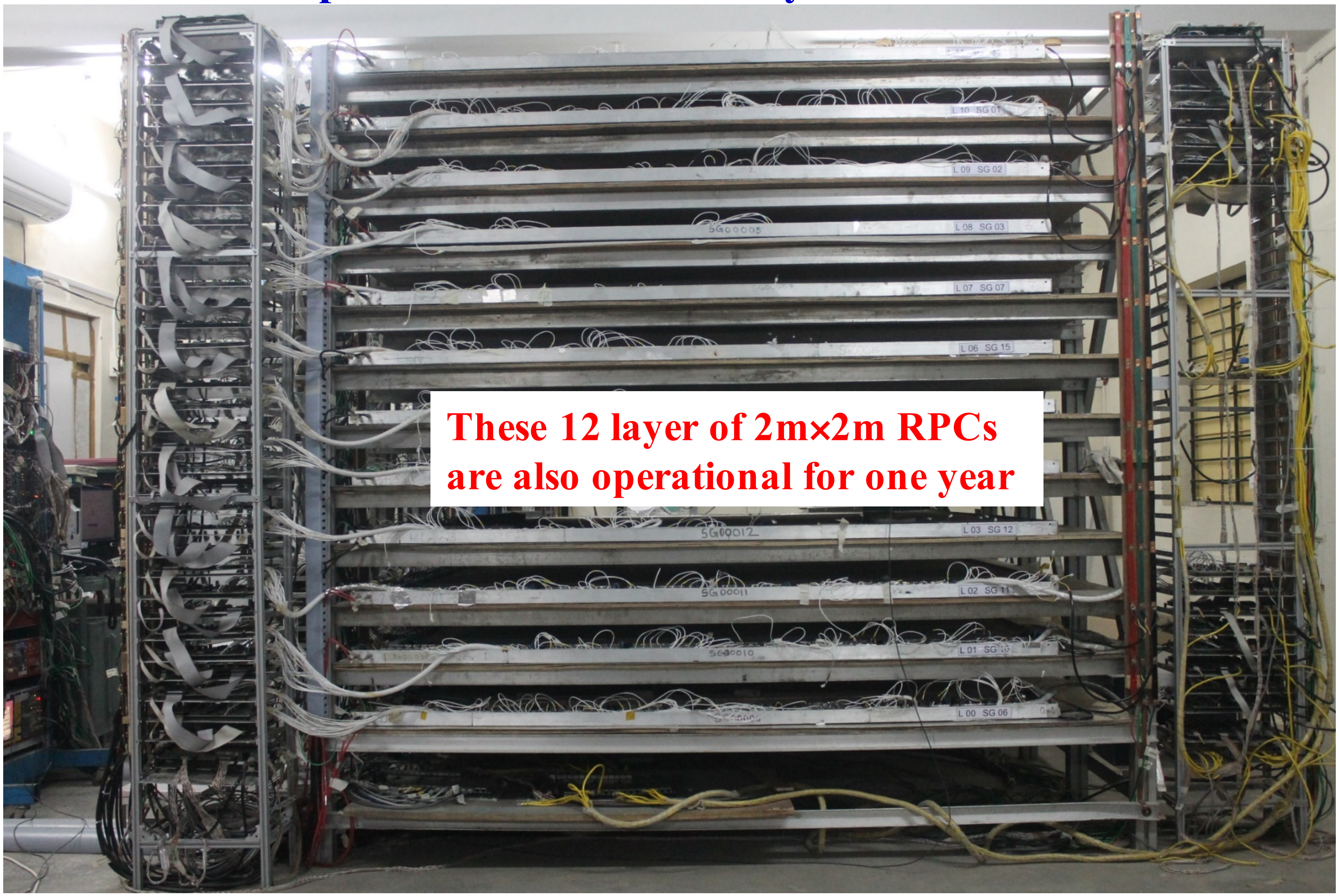
500AT : ~1.5 Tesla



- 35 Ton prototype with 12 gaps to house 1m × 1m RPCs
- Long term operational experience
- Operate both glass & bakelite RPCs
- Reconstructed muon track with & without magnetic fields.
- Stability & suitability of LV, HV & electronics.
- Lab environmental condition.

Prototype RPC Stack at TIFR

Operational since last six years

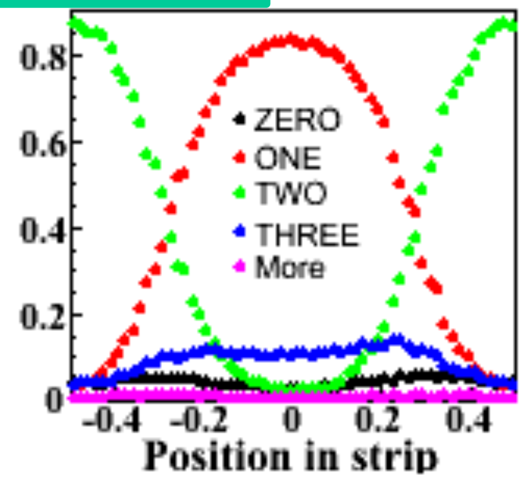


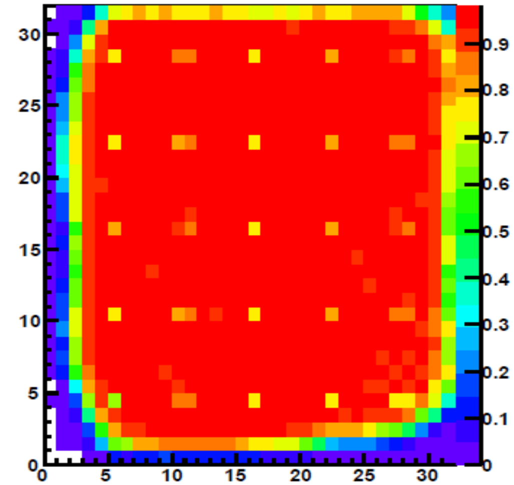
Now this system is used for developing/testing of ICAL electronics
Understood all aspects of RPC Gas gap and its signal, resolution, alignment/offset

Running Prototype RPC Stack at TIFR

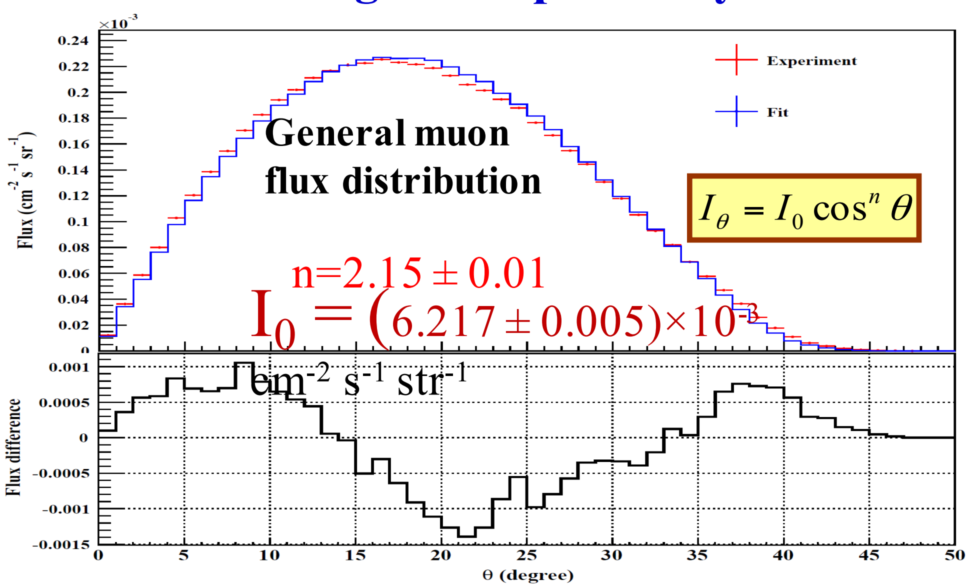
Multiplicity and position

Inefficiency due to button, dead strip, but edge effect also present

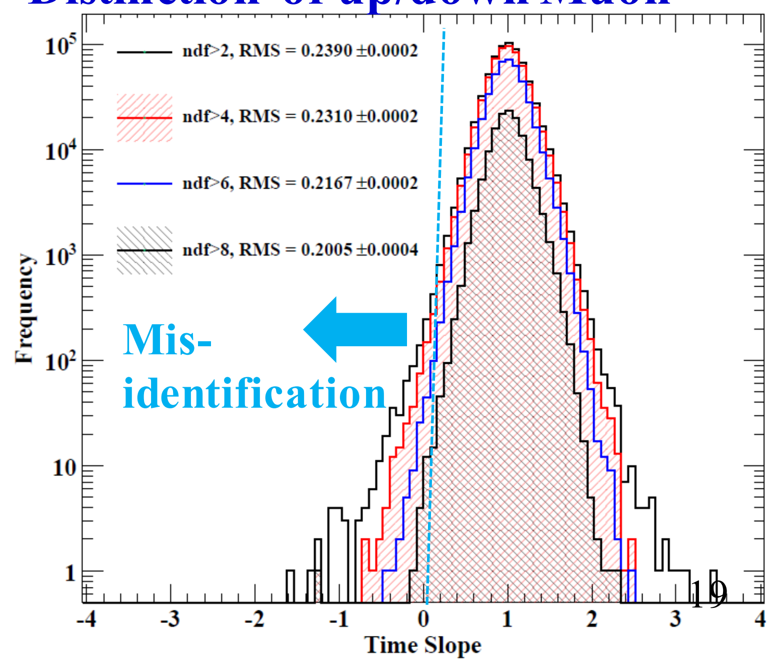




Zenith angle of muon, measurement of cosmic muon flux as well as it angular dependency

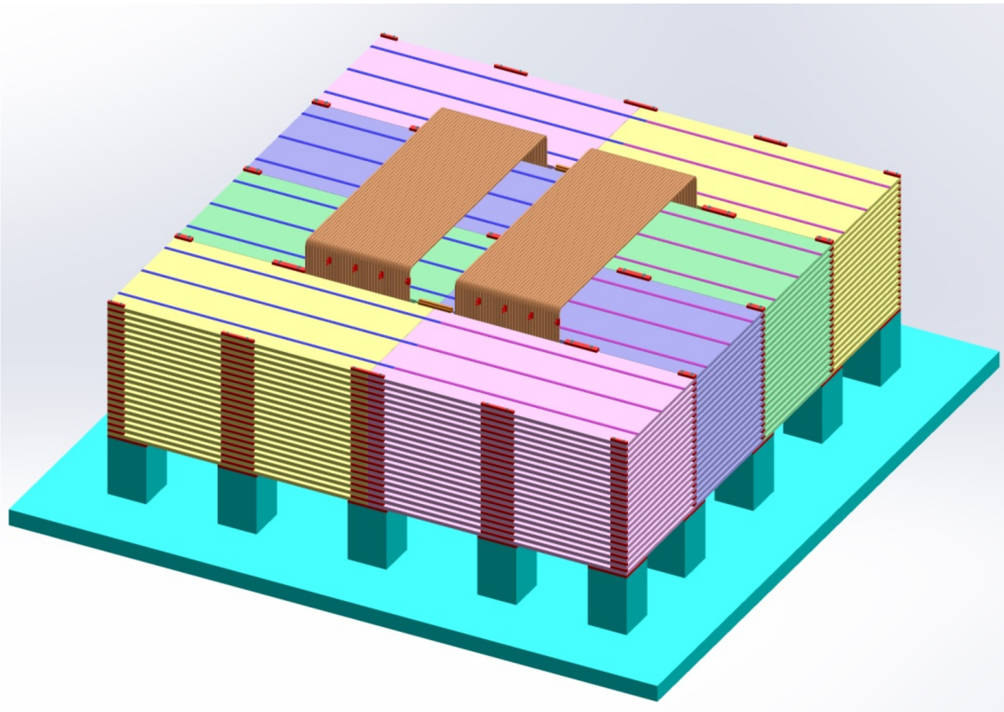


Distinction of up/down Muon



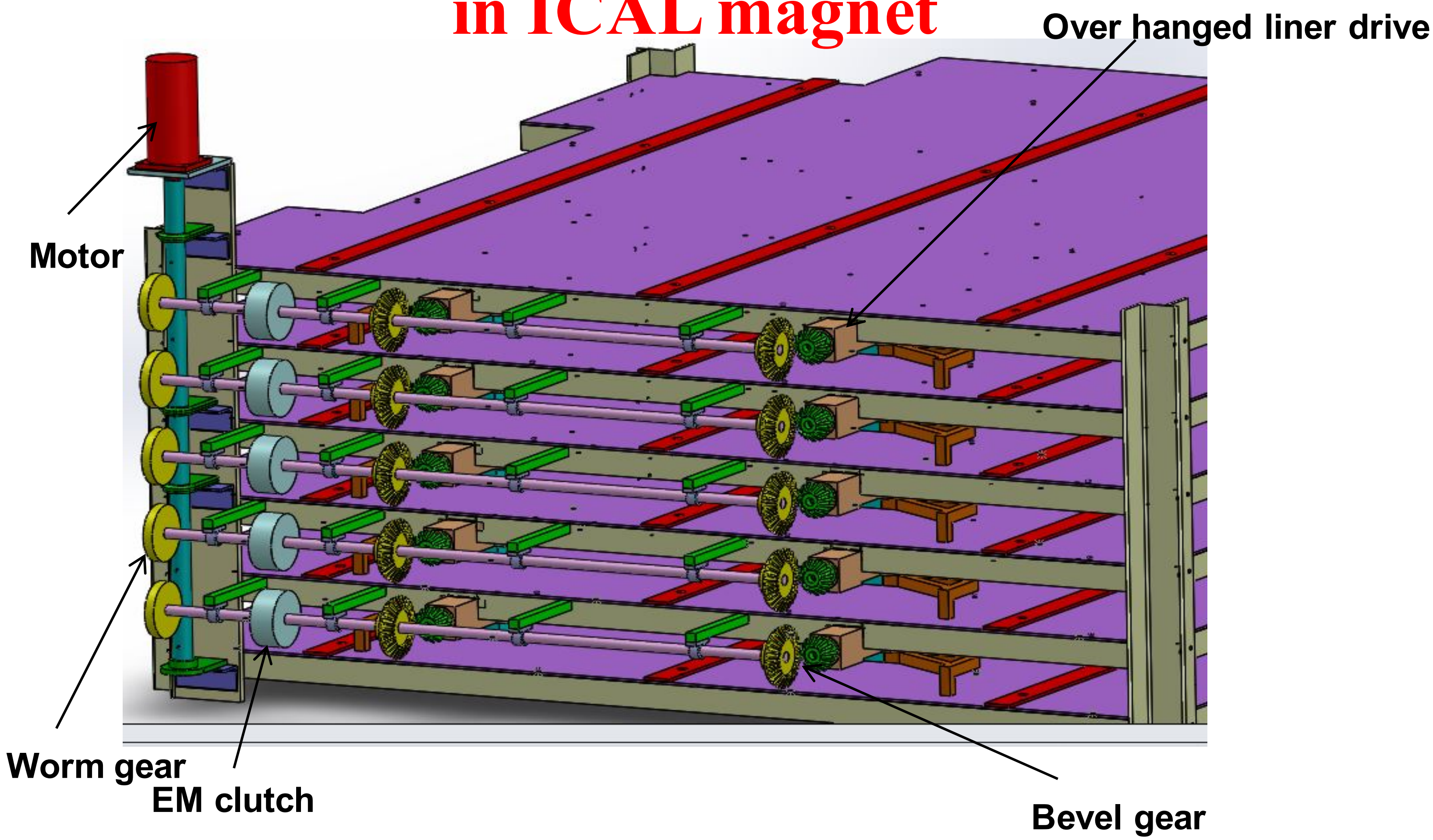
Input to detector simulation and digitisation

ICAL engg. module at IICHEP, Madurai



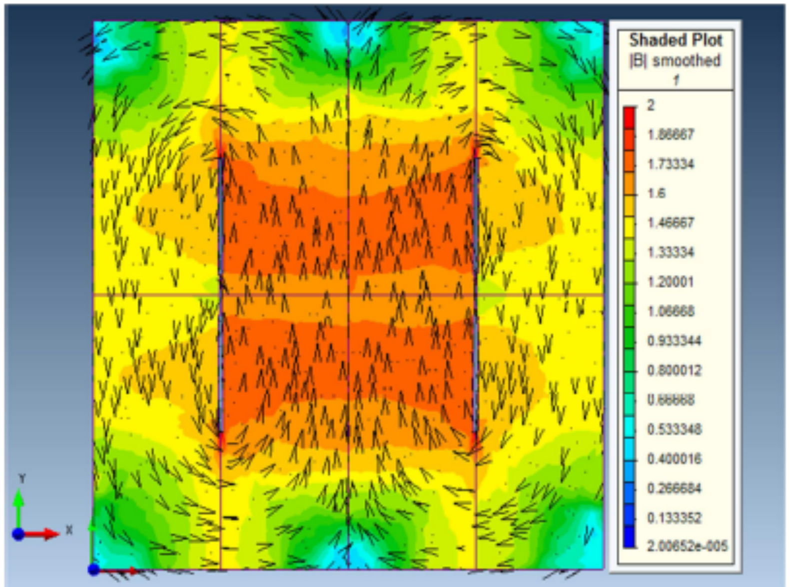
Features	Details
Magnet size (meter)	8 x 8 x 2.1
Magnet weight	~ 600 ton
Iron plate size (meter)	4 x 2 x 0.056(tk)
No of iron plate layers/plates	21/168
No of RPC layers/ total RPC	20/320
No of iron plates in a layer	8
Slot length for each coil	1700 mm
No of coils /turns per coil	2/38
Ampere turns/ coil current	38000/500
RPC handling trolley	One side of ICAL magnet

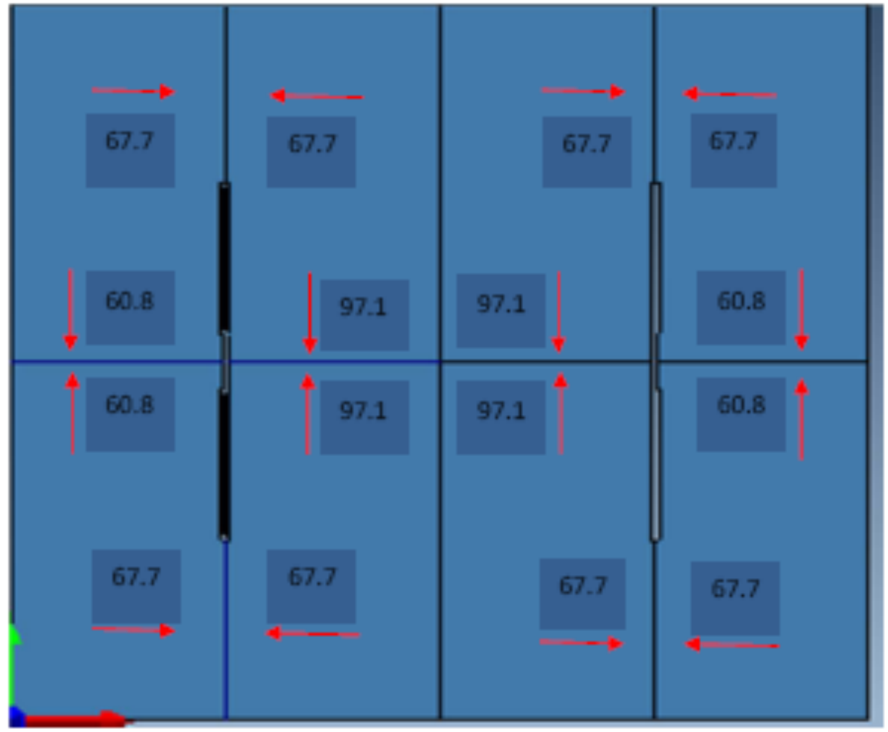
Automation of insertion & removal of RPC detector in ICAL magnet



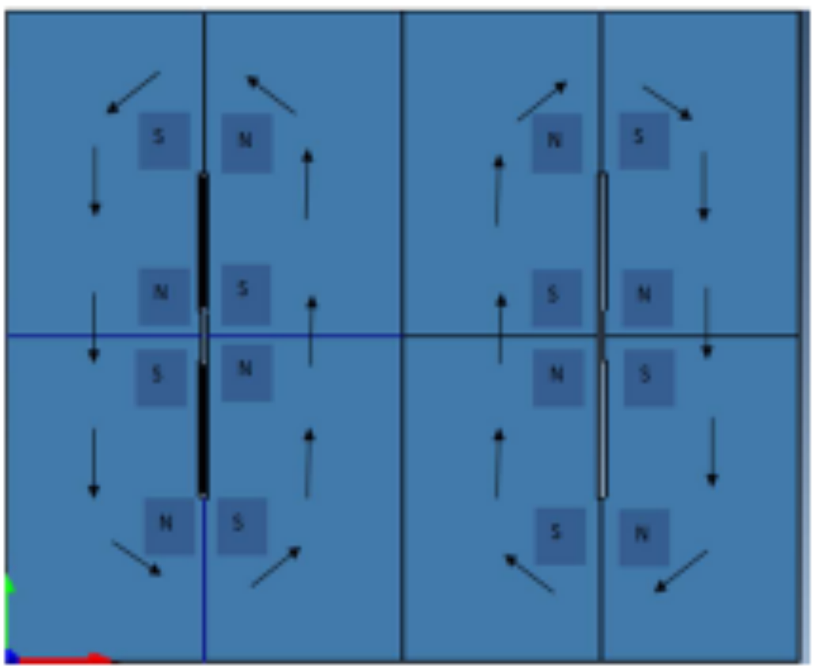
- Automatic detection of RPC tray by sensors
- Electrically driven RPC tray push/pull system
- Overloading/ jamming alarm and automatic trip system by sensors
- Laser based alignment of RPC tray with magnet gap layer.

Simulation of Engg. Module of ICAL magnet

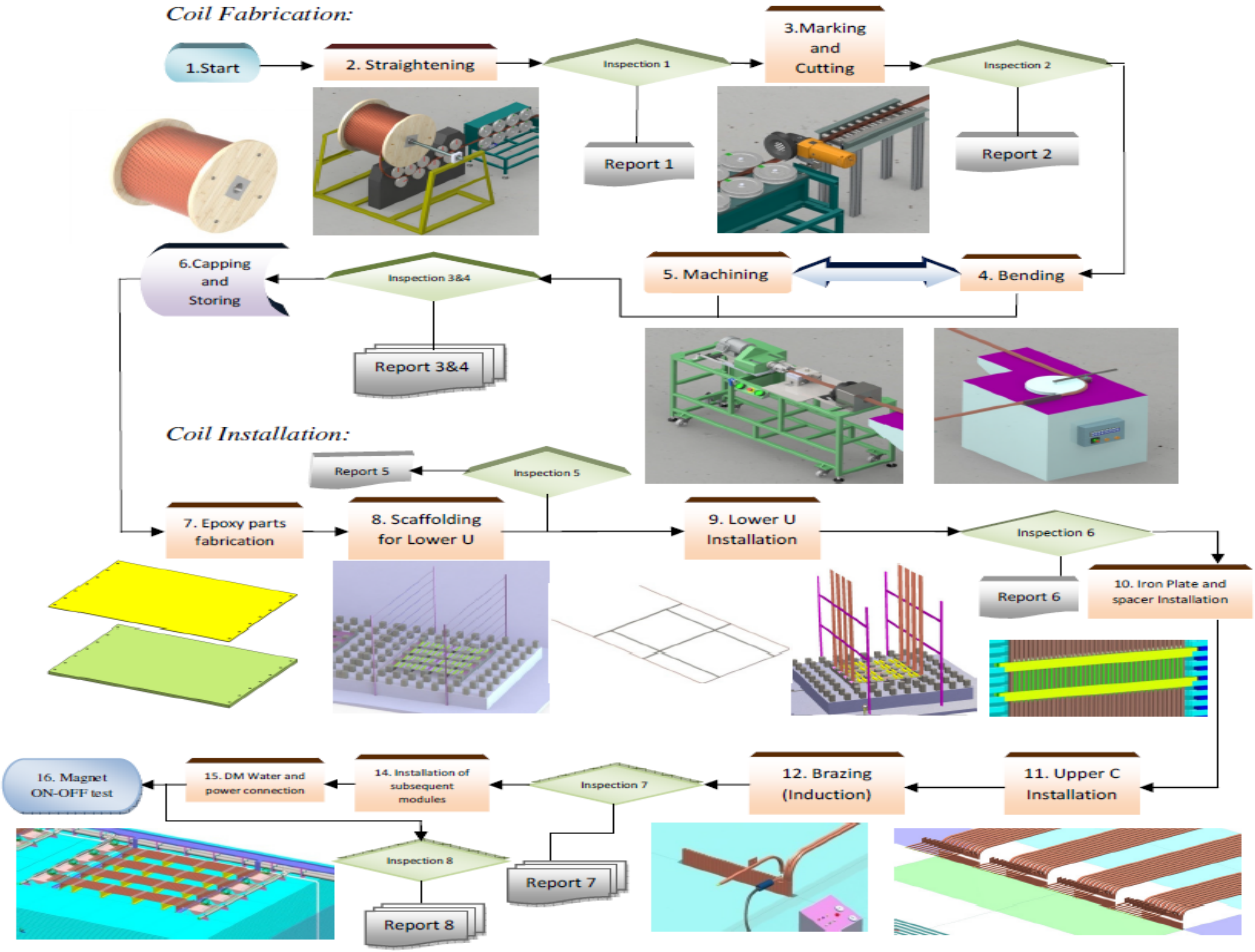




Magnetic forces in X-Y direction in KN



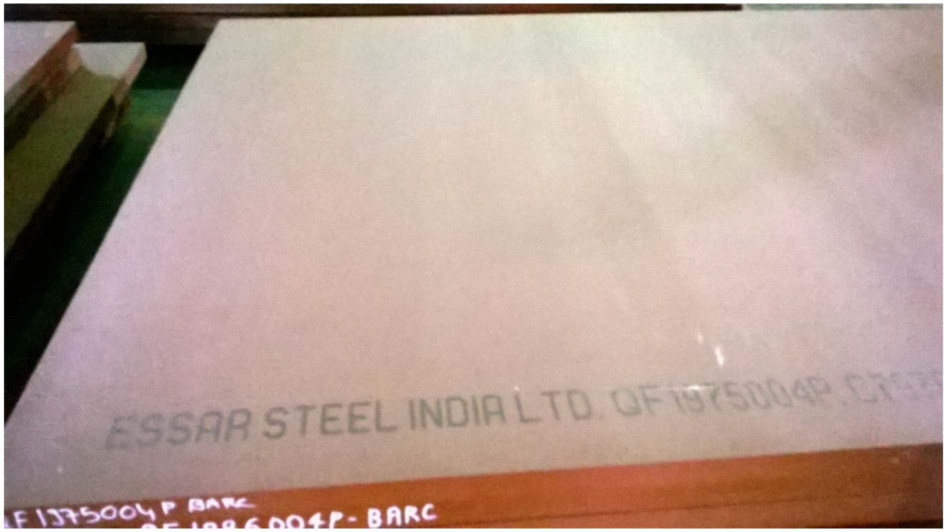
- Uniformity of field
  - For 1 T – 90.03%
  - For 1.2 T - 84.17 %
- Inductance of magnet = 1.08 henry
- Maximum force = 97.1 KN (attracting)



Coil Fabrication:
1.Start
2. Straightening
Inspection 1
Report 1
3.Marking and Cutting
Inspection 2
Report 2
4. Bending
5. Machining
Inspection 3&4
Report 3&4
6.Capping and Storing
Coil Installation:
Inspection 5
Report 5
7. Epoxy parts fabrication
8. Scaffolding for Lower U
9. Lower U Installation
Inspection 6
Report 6
10. Iron Plate and spacer Installation
11. Upper C Installation
12. Brazing (Induction)
Inspection 7
Report 7
14. Installation of subsequent modules
15. DM Water and power connection
16. Magnet ON-OFF test
Inspection 8
Report 8

Soft Iron Plates for IICHEP, Madurai

- Procurement of soft iron plates for IICHEP has been completed.
- Total 168 (for 21 layers) soft iron plates has been procured.

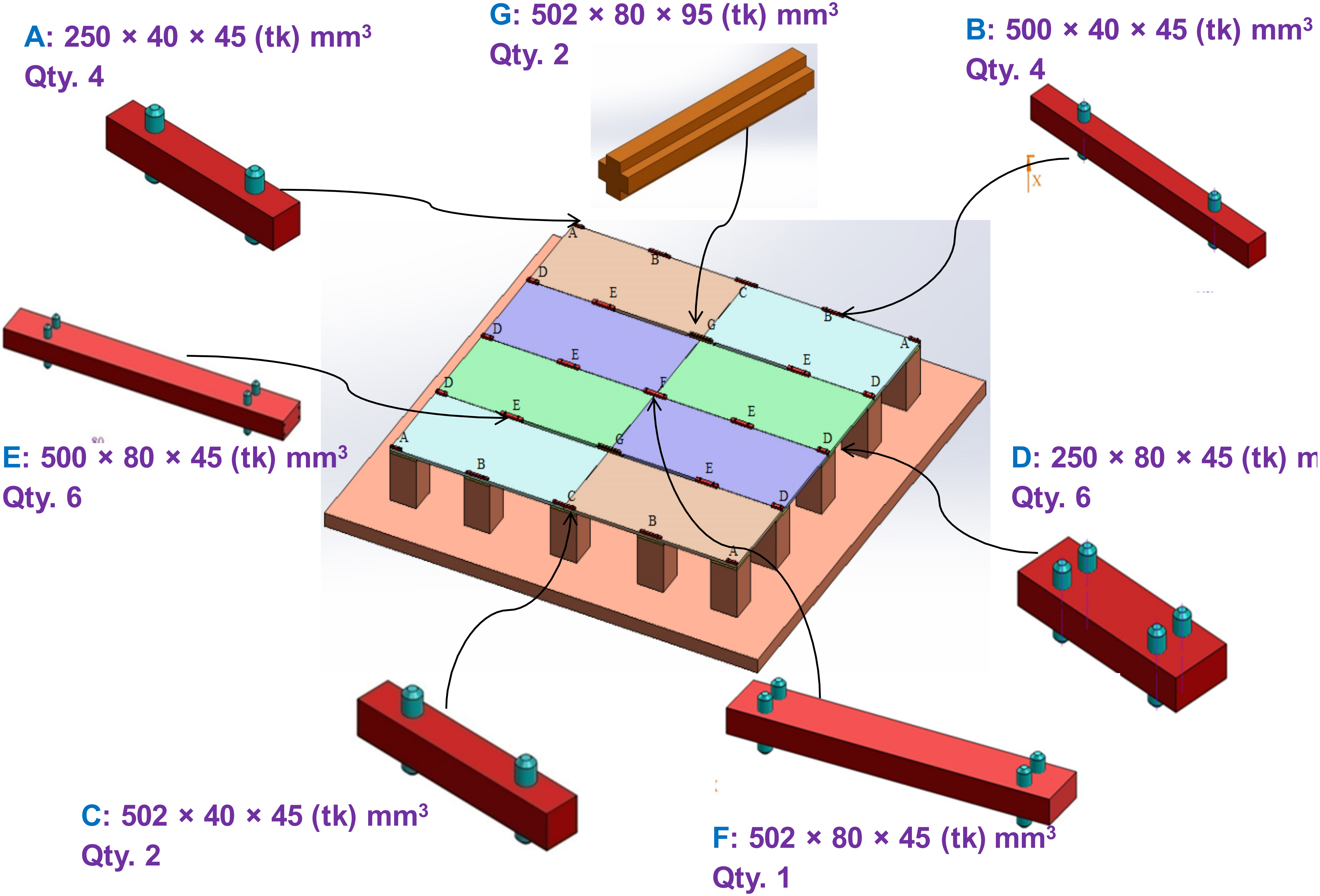


Soft iron plate

Packed soft iron plate at M/S ESSAR, Ha

Eight soft iron plates transported by 32 ton trailer in a single trip

Spacers & Locating Pin

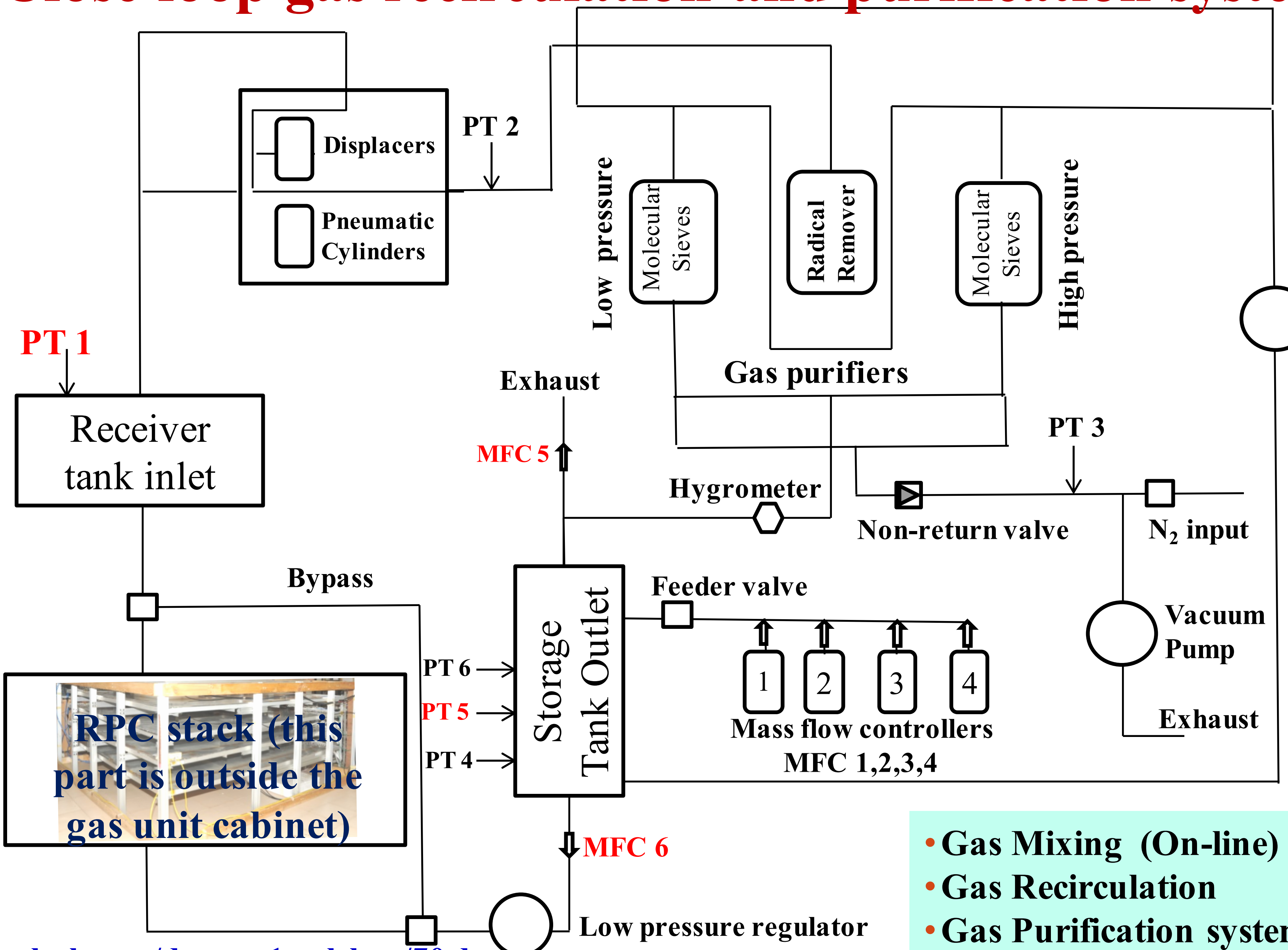


RPC handling trolley for engg. module

Parameters	Prototype
Weight	19 ton
Size	6.5 m x 3m x 12.5 m
Rail	A75
Horizontal travel	13.5 m
Vertical travel	8 m
Vertical speed	4 m/min max
Horizontal speed	4 m/min max
RPC shelf (Electrically operated)	Stroke length 750 mm
Shelf speed	92 mm/min max
Modular type lift support structure to suit height of revised prototype ICAL magnet	

Fabrication, assembly & functionality testing of RPC handling trolley. Delivered at IICHEP Madurai in April 2016

Close loop gas recirculation and purification system



1 vol. change/day 1 vol. loss/70 days

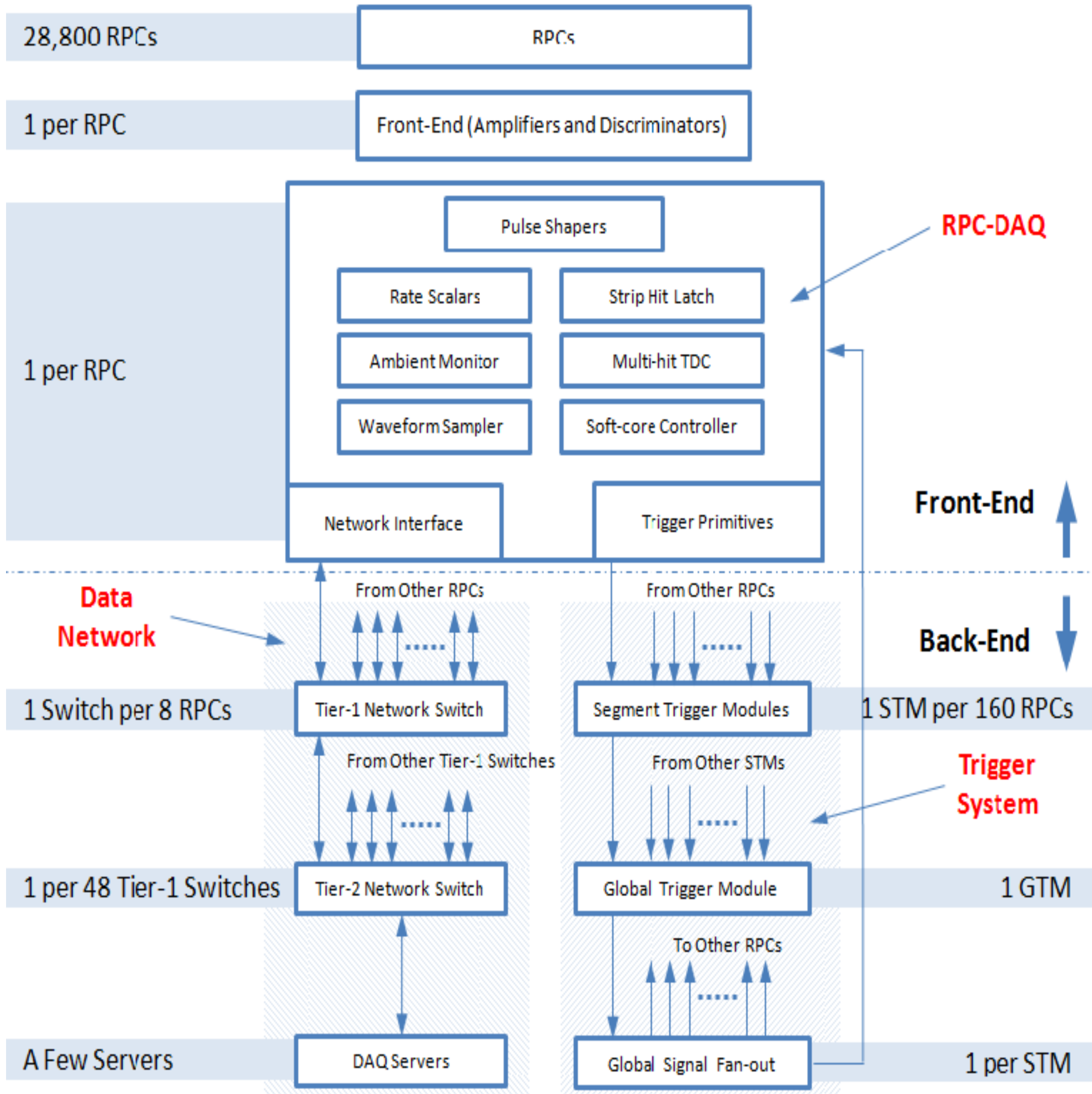
Automated pressure control, 1-3mbar above atm

- Gas Mixing (On-line)
- Gas Recirculation
- Gas Purification system
- Control System (PLC)

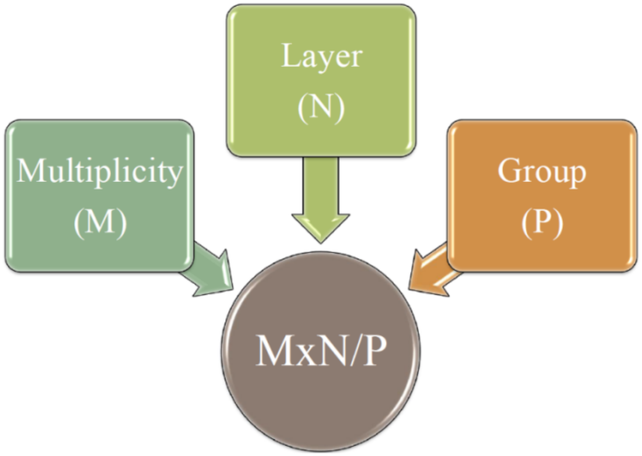
Electronics system for ICAL

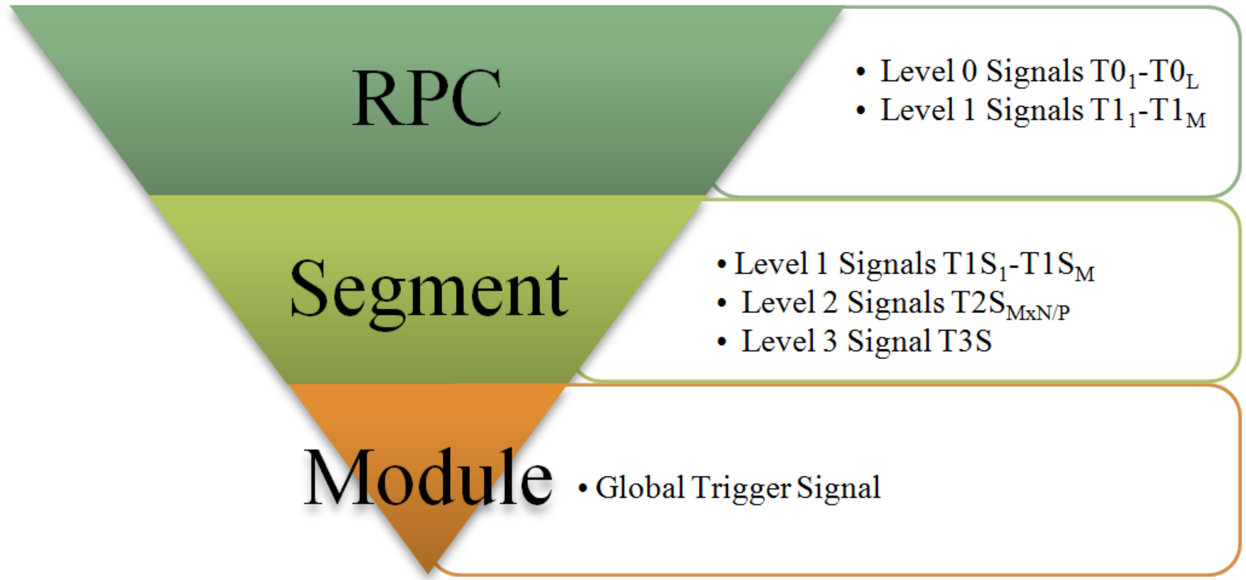
Major elements

- Front-end board
- RPCDAQ board
- Segment Trigger Module
- Global Trigger Module
- Global Trigger Driver
- Tier1 Network Switch
- Tier2 Network Switch
- DAQ Server
- VLSI, FPGA and ASIC chips; high density connectors

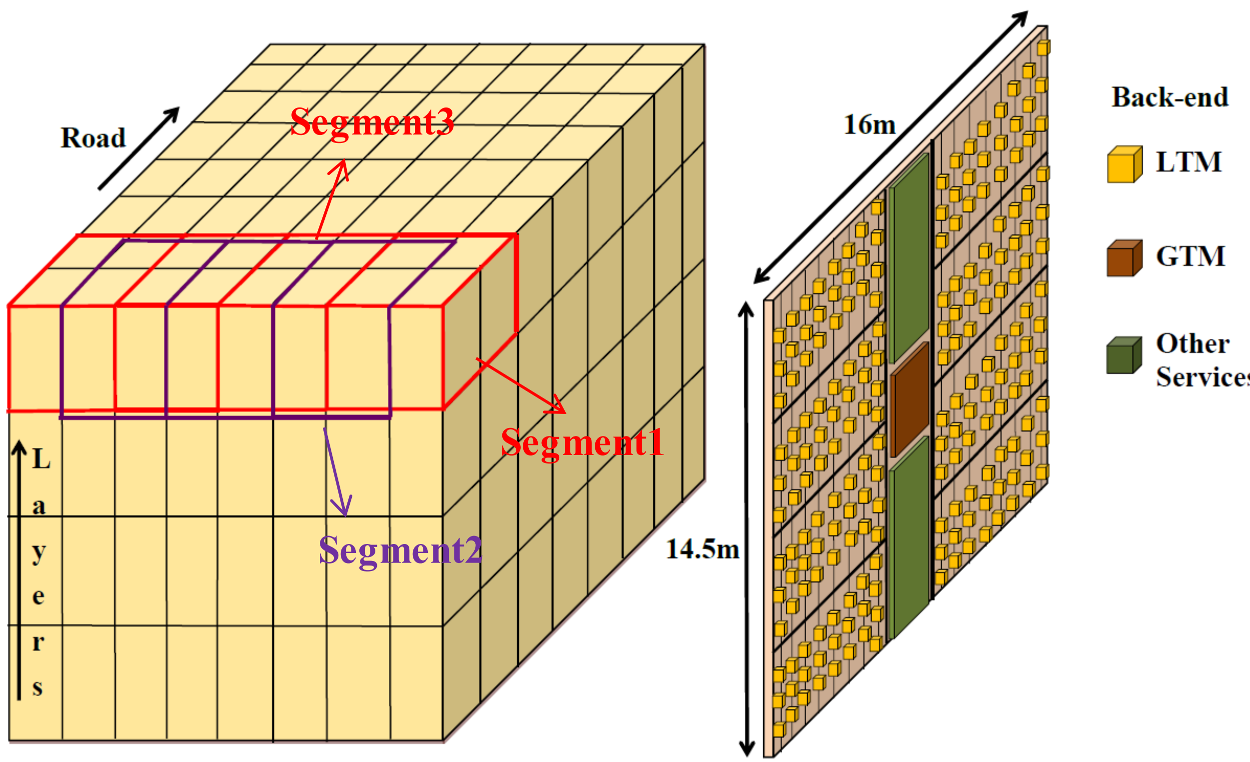


ICAL Trigger Scheme





- **Trigger criteria based on event topology alone.**
- **Distributed and hierarchical architecture.**
- **Detector module segmented to generate local trigger.**
- **Combination of local triggers produces global trigger.**
- **Global trigger latches event data.**



Detector simulation and event reconstruction

GENIE : modified

3D neutrino flux, Weighted evt

Neutrino Event Generation

$\nu_a + X \rightarrow A + B + \ldots$

Generates particles that result from a random interaction of a neutrino with matter using theoretical models .

Output:

i) Reaction Channel

ii) Vertex Information

iii) Energy & Momentum of all Particles

GEANT

Event Simulation

A + B + … through RPCs + Mag.Field

Simulate propagation of particles through the detector (RPCs + Magnetic Field)

Output:

i) x,y,z,t of the particles at their interaction point in detector

ii) Energy deposited

iii) Momentum information

Event Digitisation

(x,y,z,t) of A + B + … + noise + detector efficiency + time resolution **from operational RPC in Mumbai**

Output:

i) Digitised output of the previous stage (simulation)

Event Reconstruction

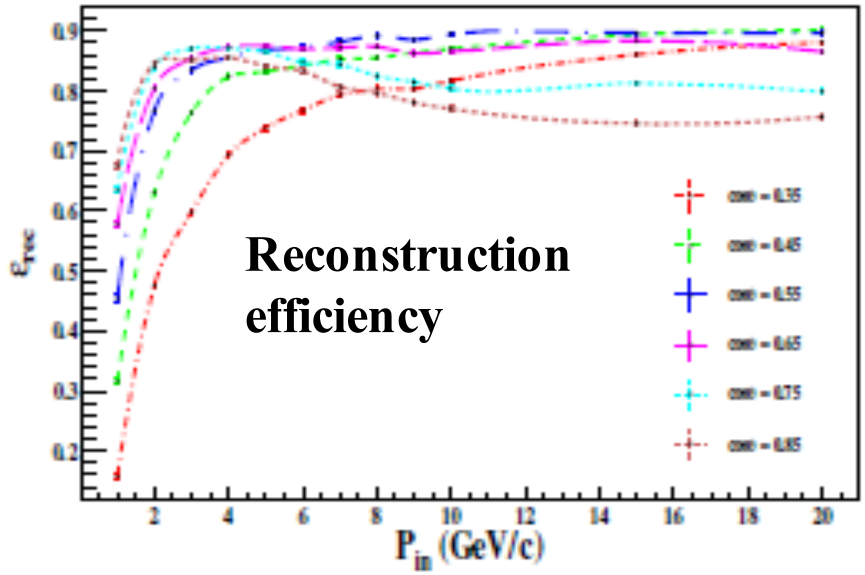
(E,p) of ν + X = (E,p) of A + B + …

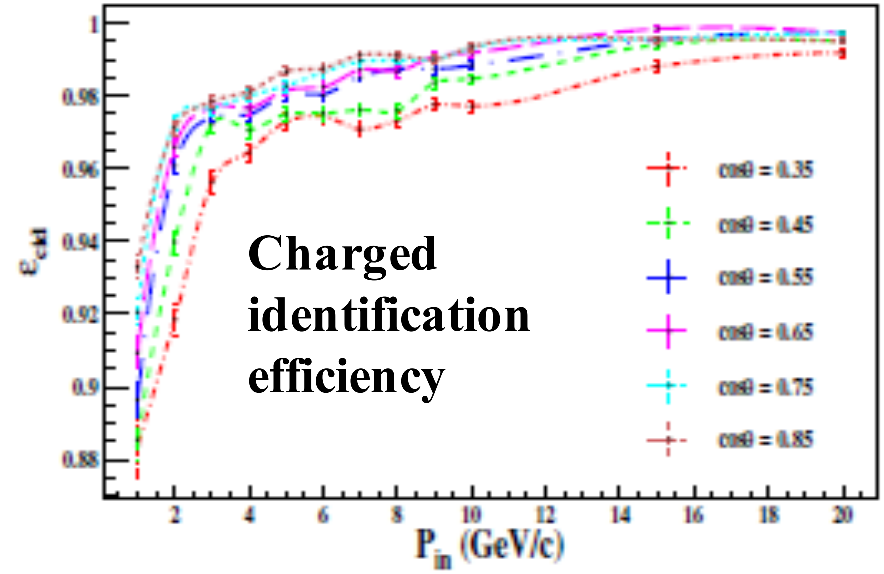
Fit the tracks of A + B + … to get their energy and momentum.

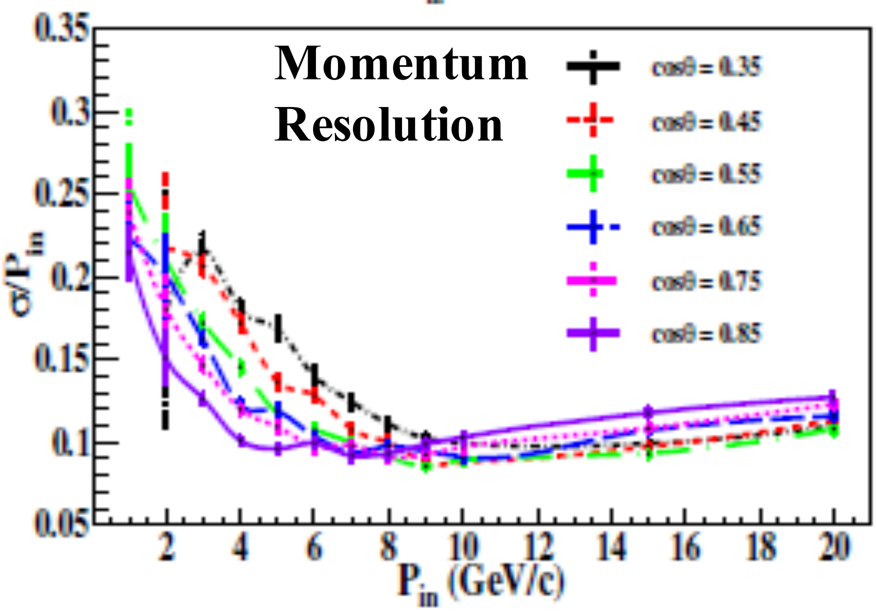
Output:

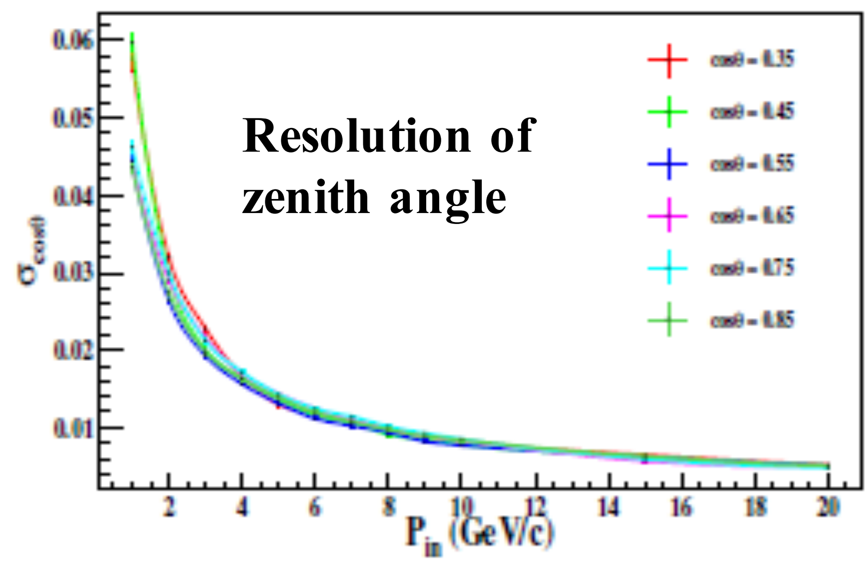
i) Energy & Momentum of the initial neutrino

ICAL response to muons









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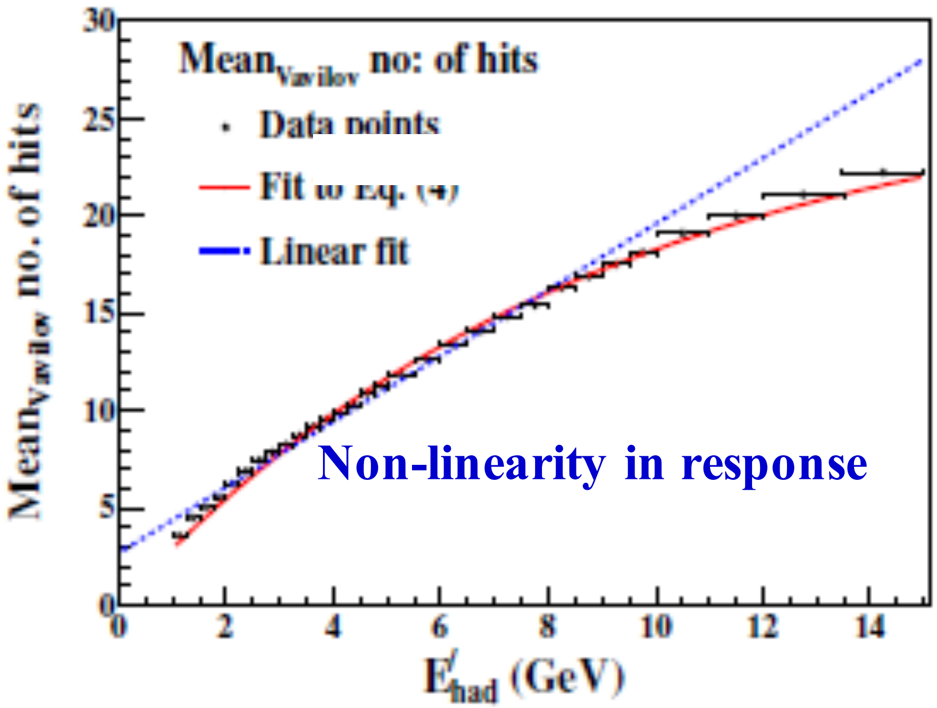
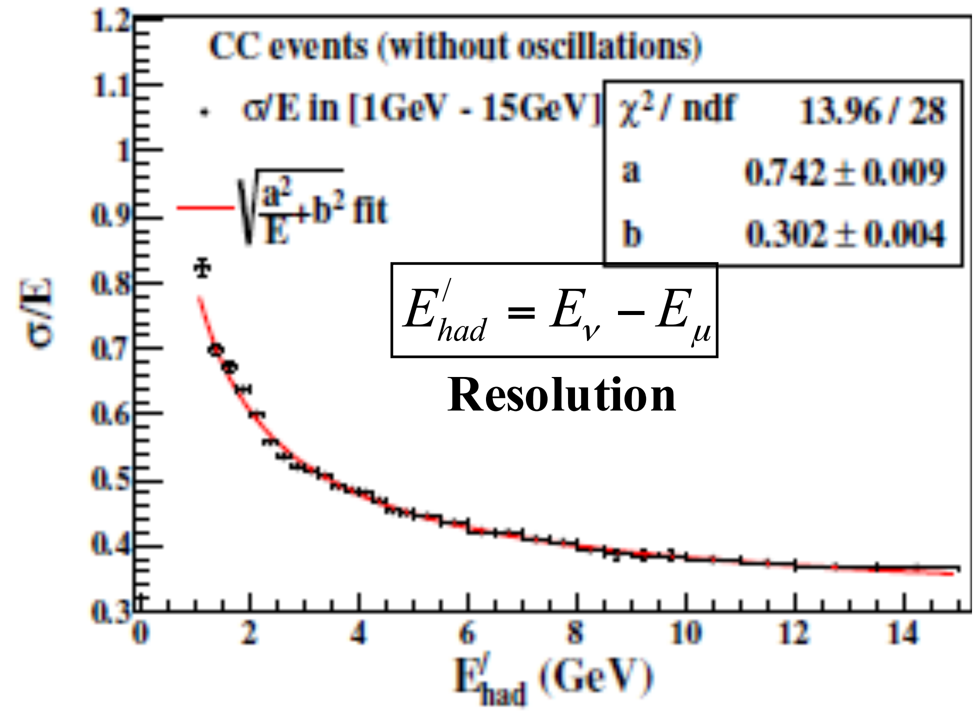
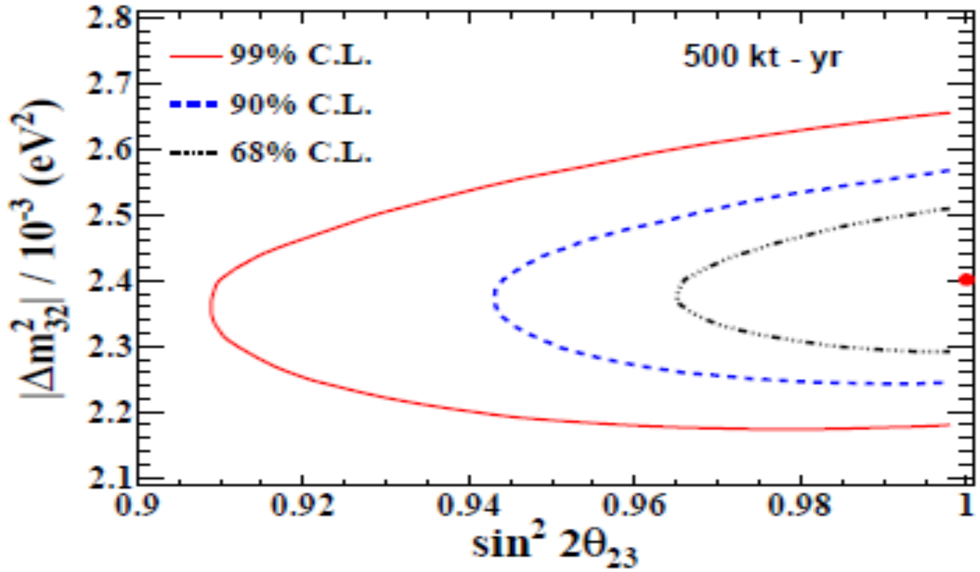
ICAL detector performance : pions

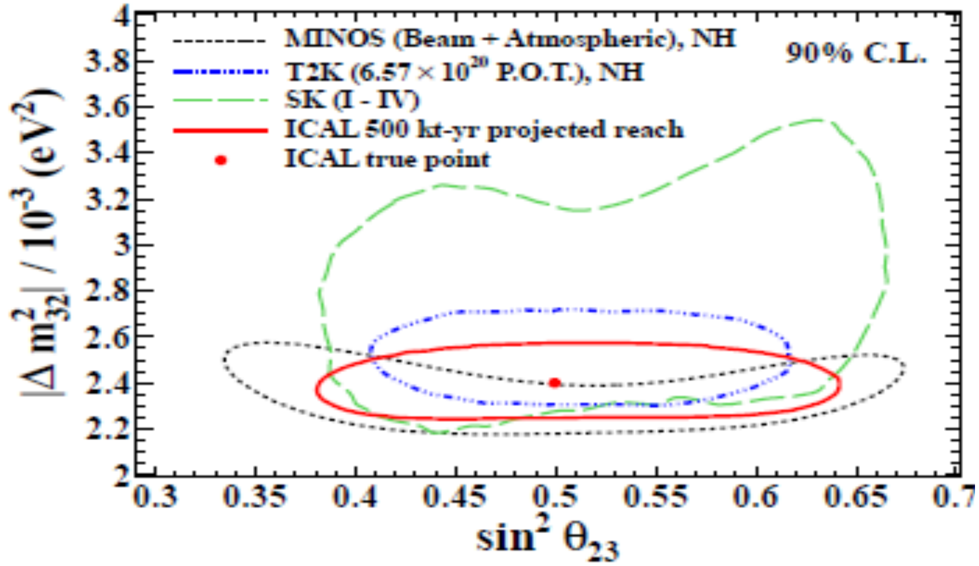




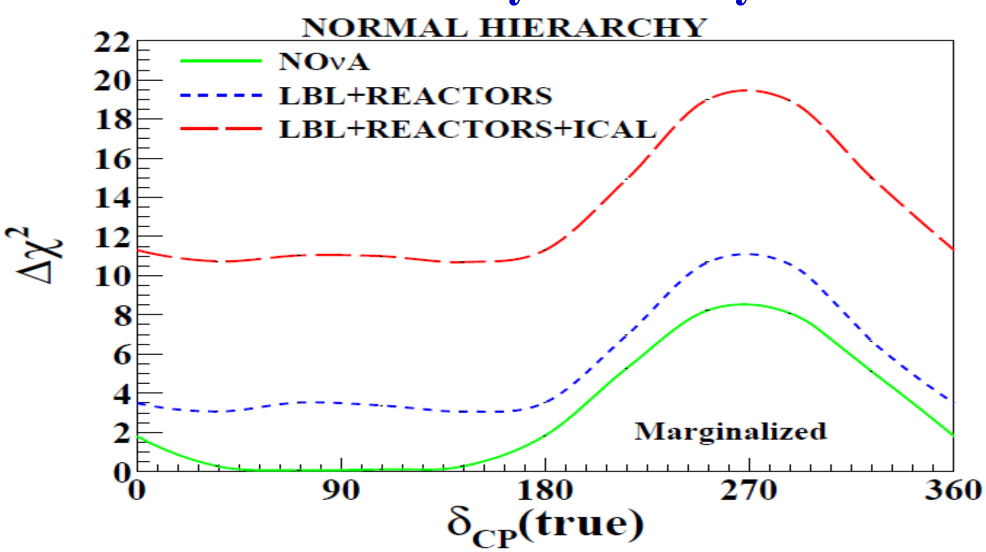
- Momentum resolution is worse in neutral energy, which is expected.
- Neutrino physics analysis was done using only information of muon as well as combined information of muon and other neutral particles.

Precision of neutrino mass matrix

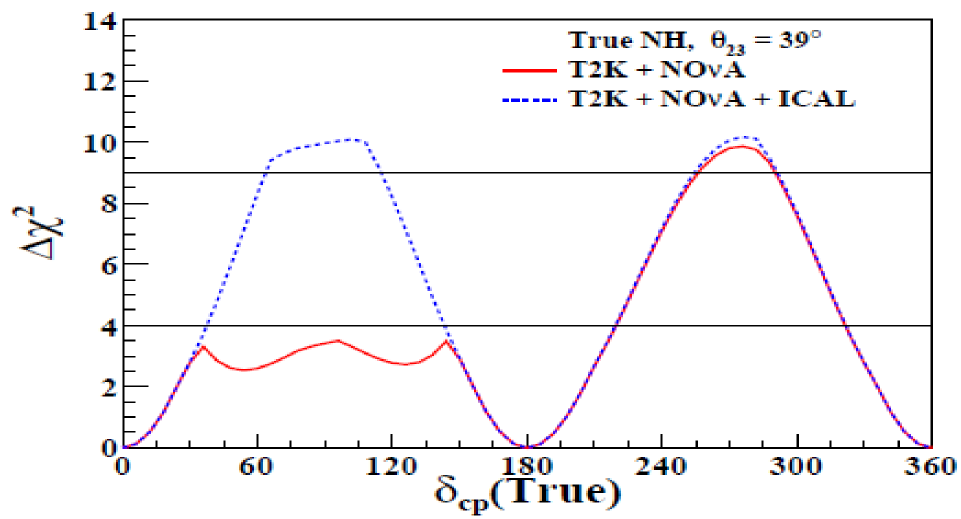




Mass hierarchy sensitivity



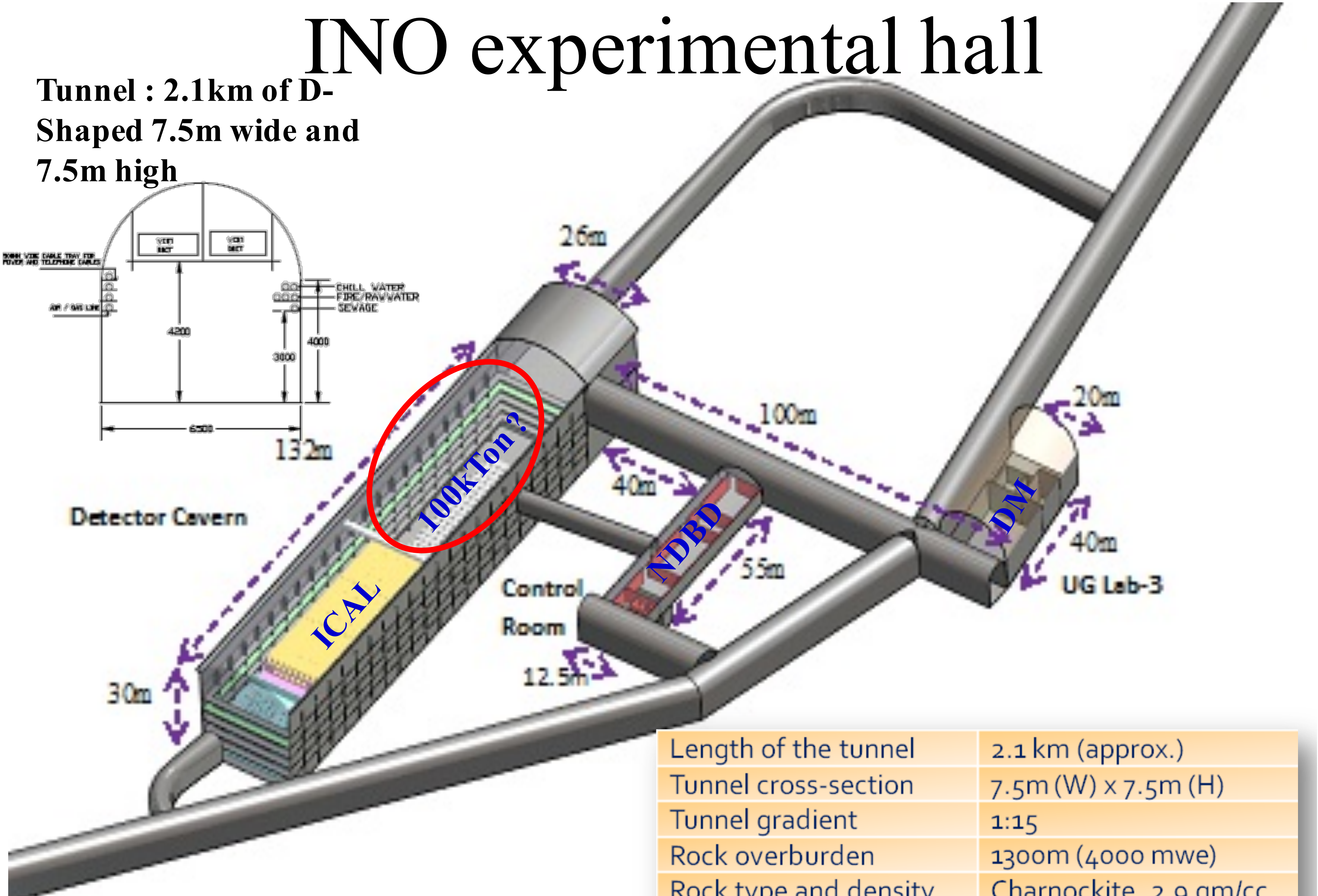
CPV discovery potential



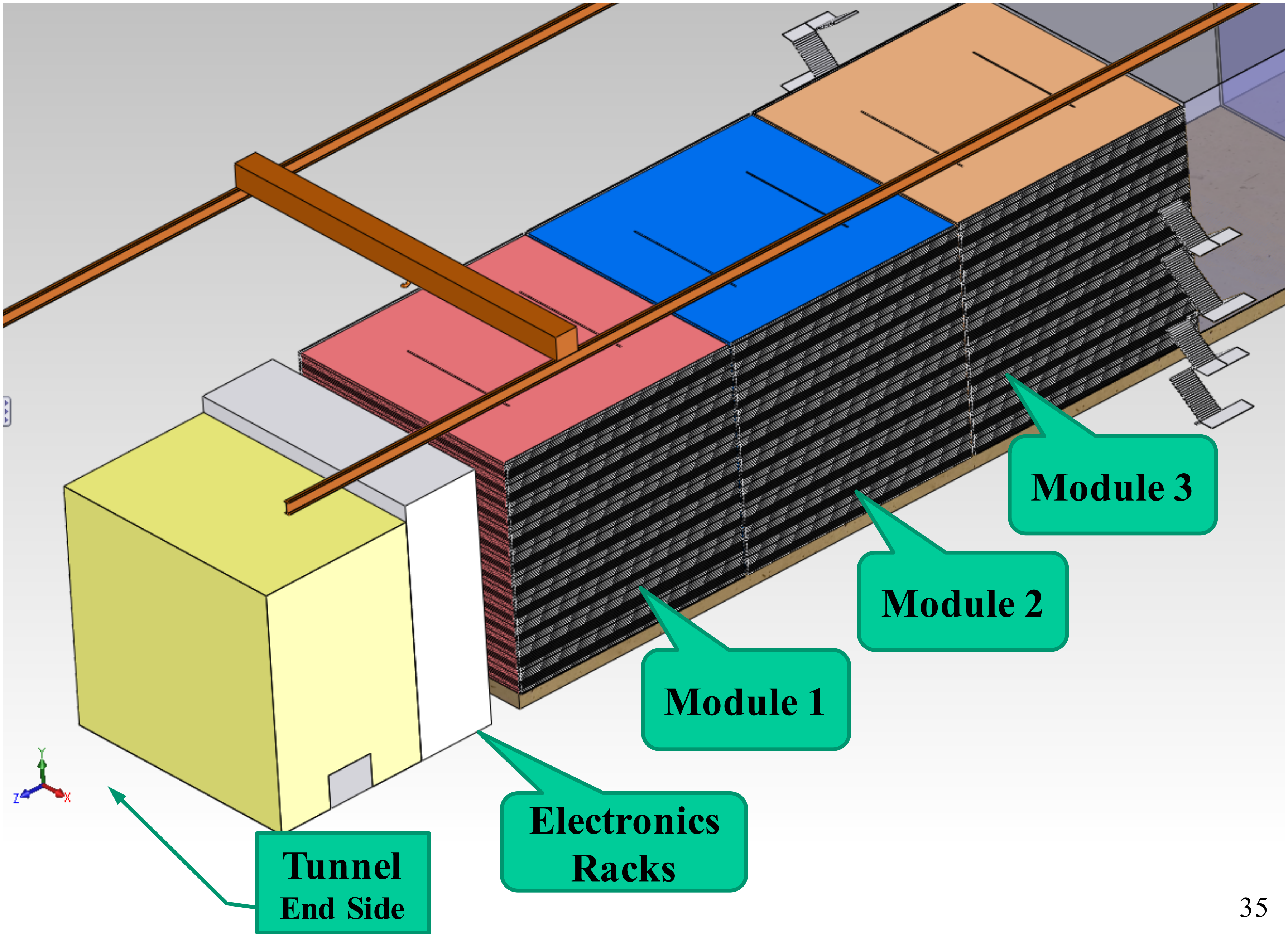
- Hierarchy sensitivity of ICAL excludes the wrong-hierarchy minimum for the CPV discovery
- ICAL will play an important role to determine these parameter more precisely

INO experimental hall

Tunnel : 2.1km of D-Shaped 7.5m wide and 7.5m high



Length of the tunnel	2.1 km (approx.)
Tunnel cross-section	7.5m (W) x 7.5m (H)
Tunnel gradient	1:15
Rock overburden	1300m (4000 mwe)
Rock type and density	Charnockite, 2.9 gm/cc
Number of caverns	3 (one big and two small)
Size of the main cavern	132m × 26m × 30m (H)

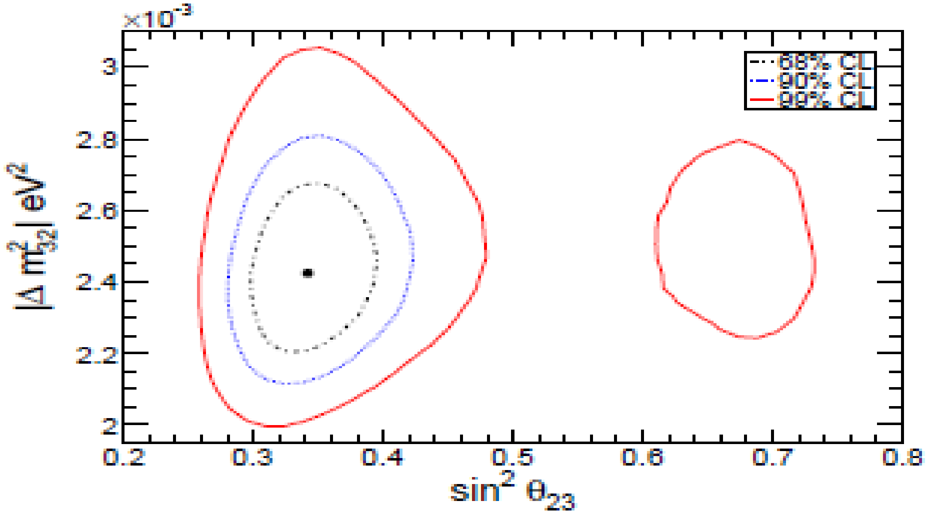

Module 3
Module 2
Module 1
Electronics Racks
Tunnel End Side

Current status

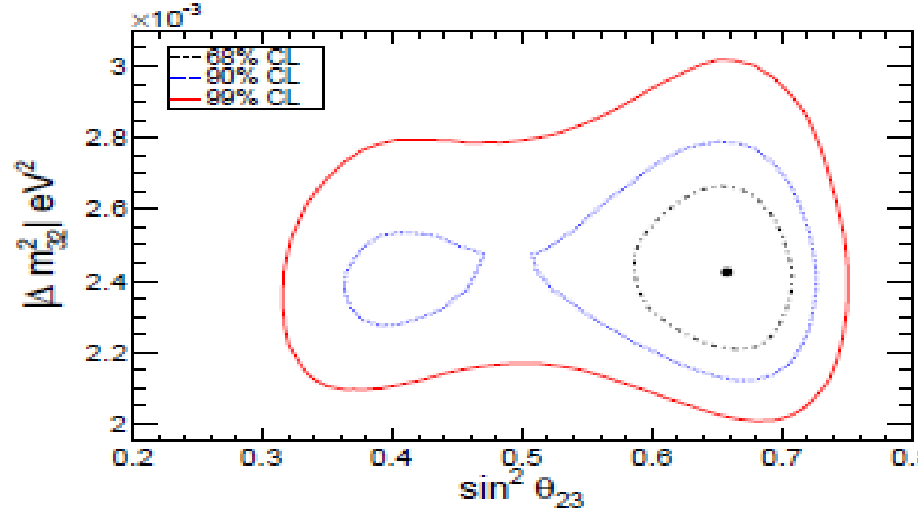
- Financial approval by Centre (12/2014) for Rs. 1583 cr. (~240M$)
- Awaiting permission from TN Govt for starting construction at IICHEP and PCB (TN) clearance for INO
- Prototype magnet: 600 tons of low carbon steel, OFHC copper conductor spools (~9.6 tons) stored at Kalpakkam, 400 glass RPCs ordered from St. Gobain
- 8m high RPC handling trolley trolley delivered
- Consultancy contract for tunnel, cavern, infrastructure on hold
- 12 layer stack of 2m × 2m glass RPCs working at Madurai
- Running 8^{th} batch if INO Graduate School

Thank you

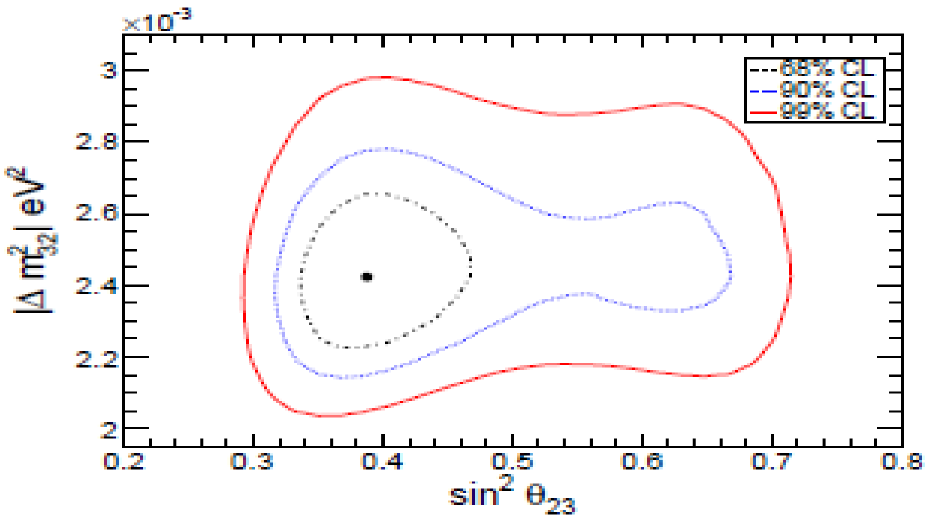
Extras



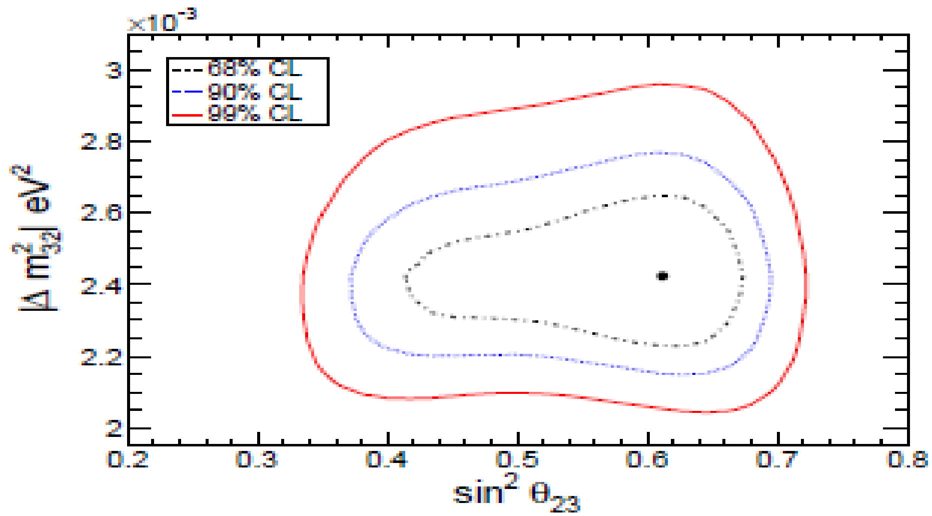
(a) $\sin^2 2\theta_{23} = 0.9$, first octant ($\sin^2 \theta_{23} = 0.342$)



(b) $\sin^2 2\theta_{23} = 0.9$, second octant ($\sin^2 \theta_{23} = 0.658$)



(c) $\sin^2 2\theta_{23}$ =0.95, first octant ($\sin^2 \theta_{23} = 0.388$)



(d) $\sin^2 2\theta_{23}$=0.95, second octant ($\sin^2 \theta_{23} = 0.612$)

- Identify the correct octant for lower value of $sin^2\theta_{23}$

INO in 13 August 2015 issue of Nature

IN FOCUS NEWS

Age of the NEUTRINO

BY ELIZABETH GIBNEY

GRAPHIC BY NIGEL HAWTIN

As researchers at CERN, Europe's particle-physics laboratory near Geneva, dream of super-high-energy colliders to explore the Higgs boson, their counterparts in other parts of the world are pivoting towards a different subatomic entity: the neutrino.

Neutrinos are more abundant than any particle other than photons, yet they interact so weakly with other matter that every second, more than 100 billion stream — mainly unnoticed — through every square centimetre of Earth. Once thought to be massless, they in fact have a minuscule mass and can change type as they travel, a bizarre and entirely unexpected feature that physicists do not fully understand (see 'An unconventional particle'). Indeed, surprisingly little is known about the neutrino. "These are the most ubiquitous matter particles in the Universe that we know of, and probably the most mysterious," says Nigel Lockyer, director of the Fermi National Accelerator Laboratory (Fermilab) in Batavia, Illinois.

Four unprecedented experiments look poised to change this. Two — one in China and one in India — already have the go-ahead, and plans to erect detectors in Japan and the United States are in the works (see 'Where they will be detected'). Buried underground to prevent interference from other particles, all four are designed to detect many more neutrinos, and to probe the switching process in more detail, than any existing experiment.

The results are expected to feed into some of the most fundamental questions in cosmology (see 'Flurry of experiments'). Some of the experiments will make their own neutrinos; all will use any they can capture from the Sun or from supernova explosions. "The age of the neutrino," Lockyer says, "could go on for a very long time."

NEUTRINO FACTORIES

Neutrinos are everywhere, generated by a variety of processes.

Fusion of hydrogen nuclei to form helium in the Sun.

Supernovae and collisions between cosmic rays and air particles in Earth's atmosphere.

Particle accelerators smashing protons into a target and fission from the radioactive decay of elements inside nuclear reactors.

WHERE THEY WILL BE DETECTED

Deep Underground Neutrino Experiment (DUNE), United States
Status: Planned
Cost: US$1 billion
Will make highest-energy neutrinos of any experiment.

Hyper-Kamiokande, Japan
Status: Planned
Cost: About $800 million
Will be the world's largest neutrino detector — it is 25 times bigger than its predecessor, Super-Kamiokande.

Jiangmen Underground Neutrino Observatory (JUNO), China
Status: Construction begun
Cost: $330 million
Sits under 700 metres of rock.

India-based Neutrino Observatory (INO), India
Status: Funding approved
Cost: $233 million
Will be largest experimental basic-science facility in India.

AN UNCONVENTIONAL PARTICLE

A neutrino (ν), or its antimatter counterpart the antineutrino, is always produced alongside an electron (e) or one of the electron's heavier cousins, the muon (μ) or tau (τ) particle — and the presence of this partner particle gives the neutrino a 'flavour'.

Unlike electrons, muons and tau particles, neutrinos do not have definite masses. Instead, every neutrino is a mixture — or quantum superposition — of three 'mass states', and those states mix in different proportions to make different flavours.

As a neutrino travels, each state contributes to its mass at a varying rate, causing the neutrino to change flavour over time. The frequency of the changes depends on the differences between the mass states, the neutrino's energy and parameters that govern how the states are allowed to mix.

Flurry of experiments

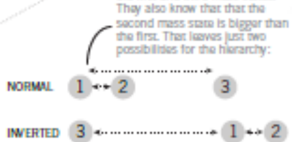
The detectors in China (JUNO) and India (INO) are designed to untangle the relationship between the three mass states, with implications for the origins of the forces of nature. By contrast, DUNE in the United States and Hyper-Kamiokande in Japan aim to spot differences in how neutrinos and antineutrinos oscillate between flavours. That could solve a second cosmological puzzle: why the Universe is made up of matter rather than antimatter. All four detectors will also hunt for a hypothesized 'sterile' neutrino.

BIG QUESTIONS

What is the mass hierarchy?

Although physicists know that neutrinos exist in three different mass states, which state is the lightest and which is the heaviest remains a mystery. Knowing that would help scientists to decide between rival theories about how the four forces of nature unite as a single force at high energies, similar to those experienced in the moments after the Big Bang.

Physicists know the differences between the first and second and the first and third mass states. They also know that that the second mass state is bigger than the first. That leaves just two possibilities for the hierarchy:



Why is there so little antimatter?

A major puzzle is why the Universe is filled with matter, rather than antimatter. Differences in how neutrinos and antineutrinos oscillate between flavours as they travel could provide a clue.

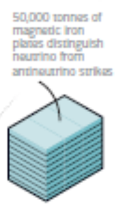
Is there a 'sterile' neutrino?

Some theories propose a fourth, sterile, neutrino. If it exists, it would interact with matter even more weakly than the other flavours, and could account for the as-yet-undetected dark matter that is thought to make up 85% of all the matter in the Universe. If neutrinos mysteriously 'disappear' at a detector, that could be a sign that they have switched into sterile neutrinos.

2020

JUNO

Will measure the rate at which antineutrinos of different energies created at the Yangjiang and Taishan nuclear power plants (53 kilometres apart) switch flavour to calculate the differences between mass states.



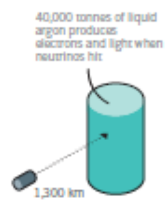
INO

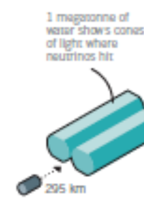
Will detect neutrinos and antineutrinos produced by cosmic rays from the other side of Earth. If the journey boosts neutrino switching, this implies a normal mass hierarchy; if antineutrino switching speeds up, the inverted hierarchy is likely.

2025

DUNE

Will send neutrinos of different energies from Fermilab to the Sanford Underground Research Facility in South Dakota. Physicists will record differences in the way neutrinos and antineutrinos oscillate and how this depends on their energy.





Hyper-Kamiokande

Neutrinos and antineutrinos will travel from the Japan Proton Accelerator Research Complex (J-Parc) in Tokaimura. Particles will be of a single energy, selected to maximize the detection of flavour switching over the distance from J-Parc.